US009331765B2

(12) **United States Patent**
Mobasher et al.

(10) **Patent No.: US 9,331,765 B2**
(45) **Date of Patent: *May 3, 2016**

(54) **MIXED RANK DOWNLINK MULTI-USER INTERFERENCE ALIGNMENT SCHEME**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 163 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **13/822,661**

(22) PCT Filed: **Feb. 1, 2011**
(Under 37 CFR 1.47)

(86) PCT No.: **PCT/IB2011/050427**

§ 371 (c)(1),
(2), (4) Date: **Feb. 7, 2014**

(87) PCT Pub. No.: **WO2012/104676**

PCT Pub. Date: **Aug. 9, 2012**

(65) **Prior Publication Data**

US 2014/0348253 A1 Nov. 27, 2014

(51) **Int. Cl.**
H04B 7/06 (2006.01)
H04B 7/04 (2006.01)
H04W 24/10 (2009.01)

(52) **U.S. Cl.**
CPC ***H04B 7/063*** (2013.01); ***H04B 7/0452*** (2013.01); ***H04B 7/0632*** (2013.01); ***H04B 7/0634*** (2013.01); *H04W 24/10* (2013.01)

(58) **Field of Classification Search**
CPC H04B 7/02; H04B 7/04; H04B 7/0408; H04B 7/0413; H04B 7/0417; H04B 7/0421; H04B 7/0452; H04B 7/0456; H04B 7/0491; H04B 7/0619; H04B 7/063; H04B 7/0632; H04B 7/0634; H04B 7/0639; H04B 7/066; H04B 7/0663; H04B 7/0665; H04B 7/08; H04B 7/0842; H04B 7/0862; H04W 24/10
USPC 375/259, 260, 262, 265, 267, 299, 347; 370/208, 210, 310, 328–330, 343, 345
See application file for complete search history.

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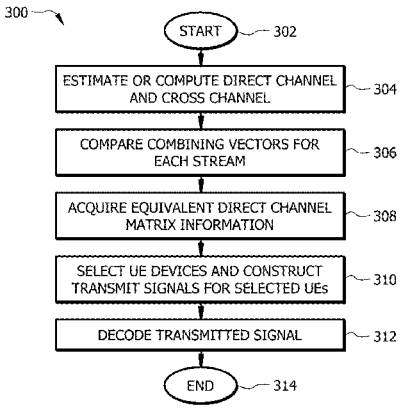
(57) **ABSTRACT**

A method, system and device are provided for using an indexed list of linearly independent, predetermined vectors $V_{ref}=\{v_{ref}^{1},\ldots,v_{ref}^{M}\}$ and channel knowledge H, G from each transmitter to compute and feedback equivalent channel matrix information $H_{i,j}^{eq}$ to its affiliated transmitter based on the assigned/determined rank of the receiver. With this information, each transmitter selects L_i receivers and constructs a transmitted signal by applying a selected precoding matrix to the mixed rank data, thereby eliminating interference to the rest of the receivers in the network.

25 Claims, 7 Drawing Sheets



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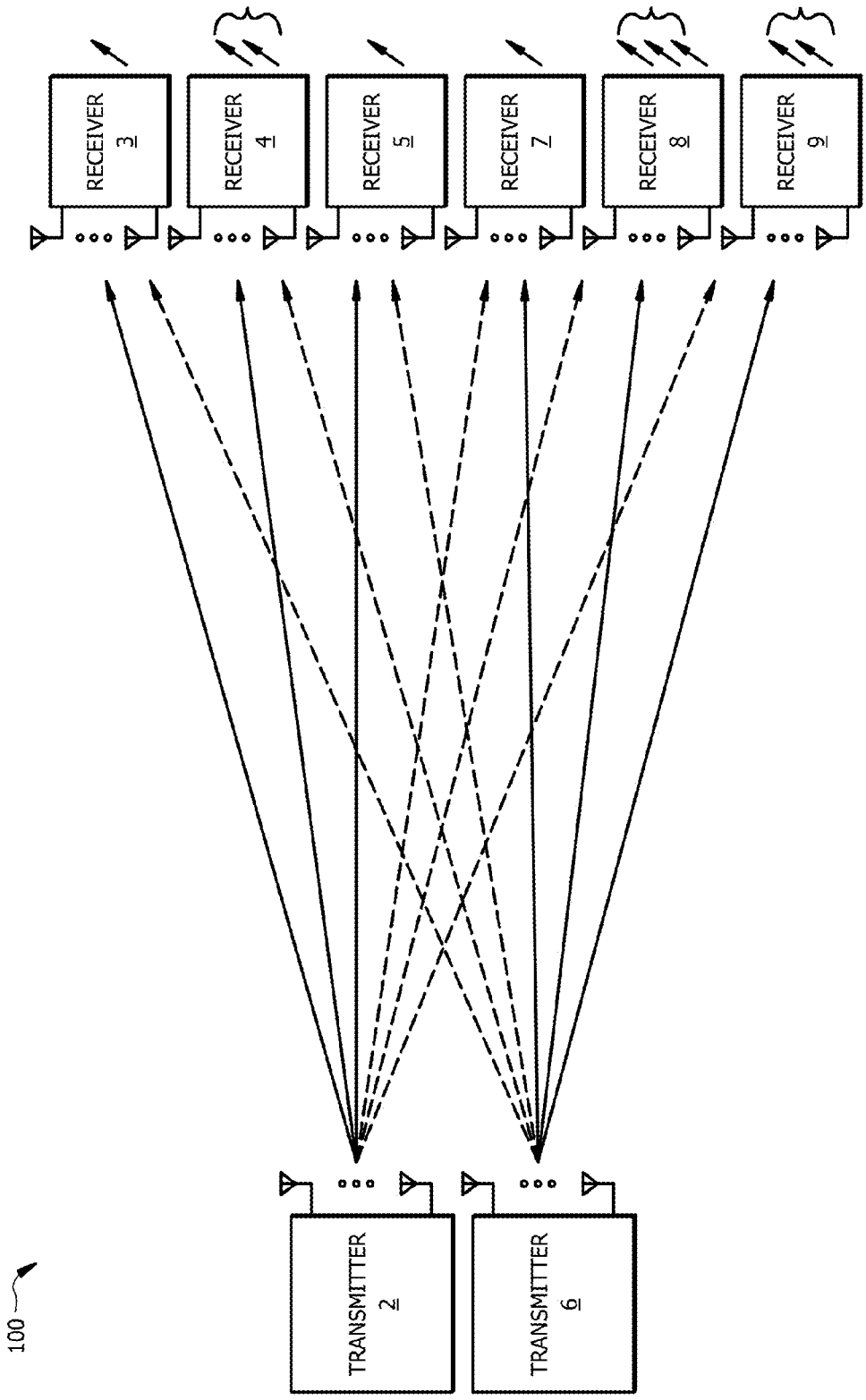
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RECEIVER 7
RECEIVER 8
RECEIVER 9
TRANSMITTER 2
TRANSMITTER 6
100

FIG. 1

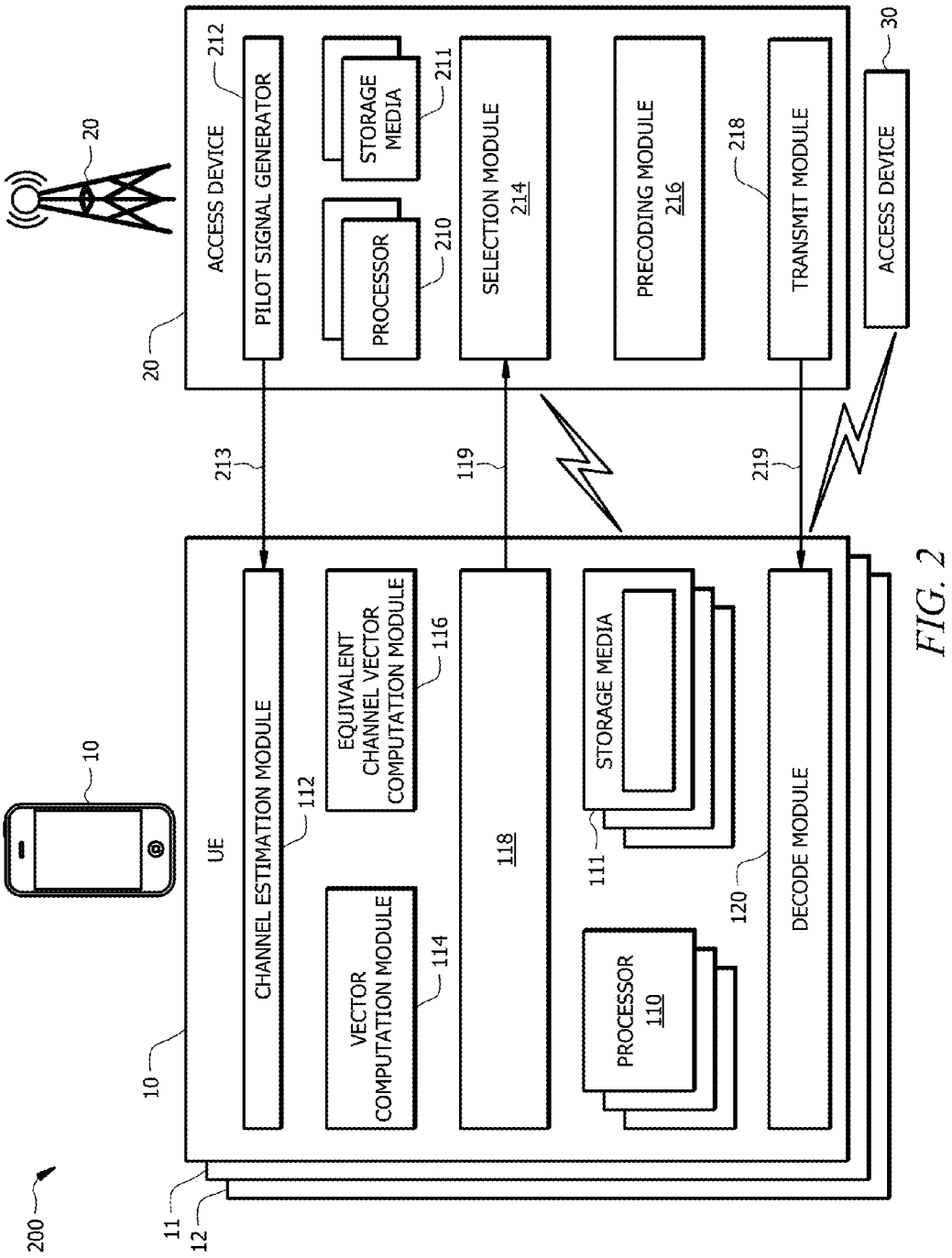
200
10
20
ACCESS DEVICE
212
PILOT SIGNAL GENERATOR
STORAGE MEDIA
211
PROCESSOR
210
SELECTION MODULE
214
PRECODING MODULE
216
218
TRANSMIT MODULE
ACCESS DEVICE
30
213
119
219
UE
CHANNEL ESTIMATION MODULE
112
EQUIVALENT CHANNEL VECTOR COMPUTATION MODULE
116
VECTOR COMPUTATION MODULE
114
118
STORAGE MEDIA
111
PROCESSOR
110
120
DECODE MODULE
11
12

FIG. 2

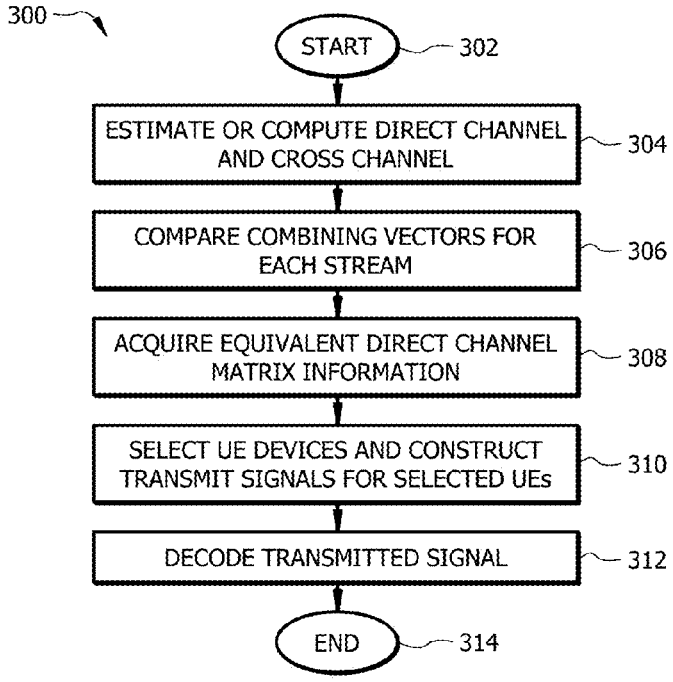
300
START
302
ESTIMATE OR COMPUTE DIRECT CHANNEL AND CROSS CHANNEL
304
COMPARE COMBINING VECTORS FOR EACH STREAM
306
ACQUIRE EQUIVALENT DIRECT CHANNEL MATRIX INFORMATION
308
SELECT UE DEVICES AND CONSTRUCT TRANSMIT SIGNALS FOR SELECTED UEs
310
DECODE TRANSMITTED SIGNAL
312
END
314

FIG. 3

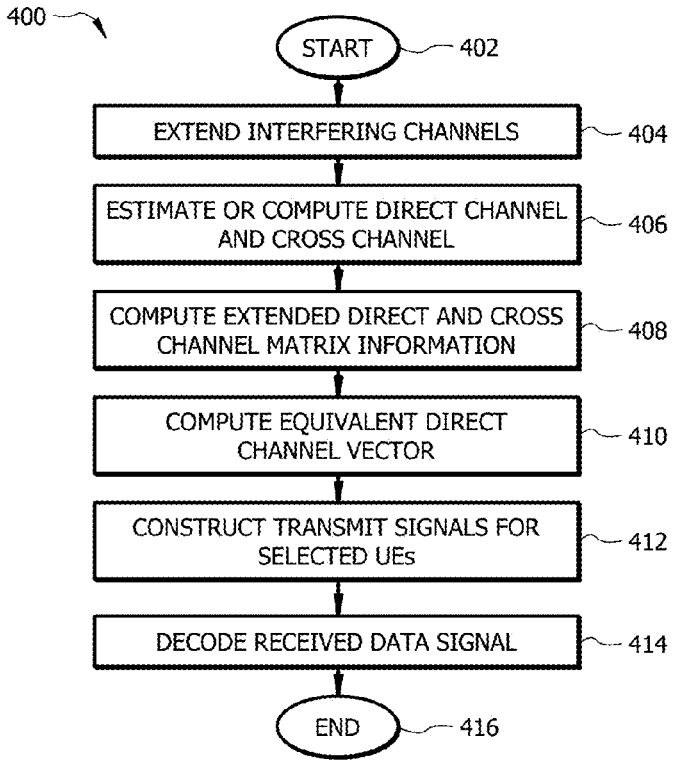
400
START
402
EXTEND INTERFERING CHANNELS
404
ESTIMATE OR COMPUTE DIRECT CHANNEL AND CROSS CHANNEL
406
COMPUTE EXTENDED DIRECT AND CROSS CHANNEL MATRIX INFORMATION
408
COMPUTE EQUIVALENT DIRECT CHANNEL VECTOR
410
CONSTRUCT TRANSMIT SIGNALS FOR SELECTED UEs
412
DECODE RECEIVED DATA SIGNAL
414
END
416

FIG. 4

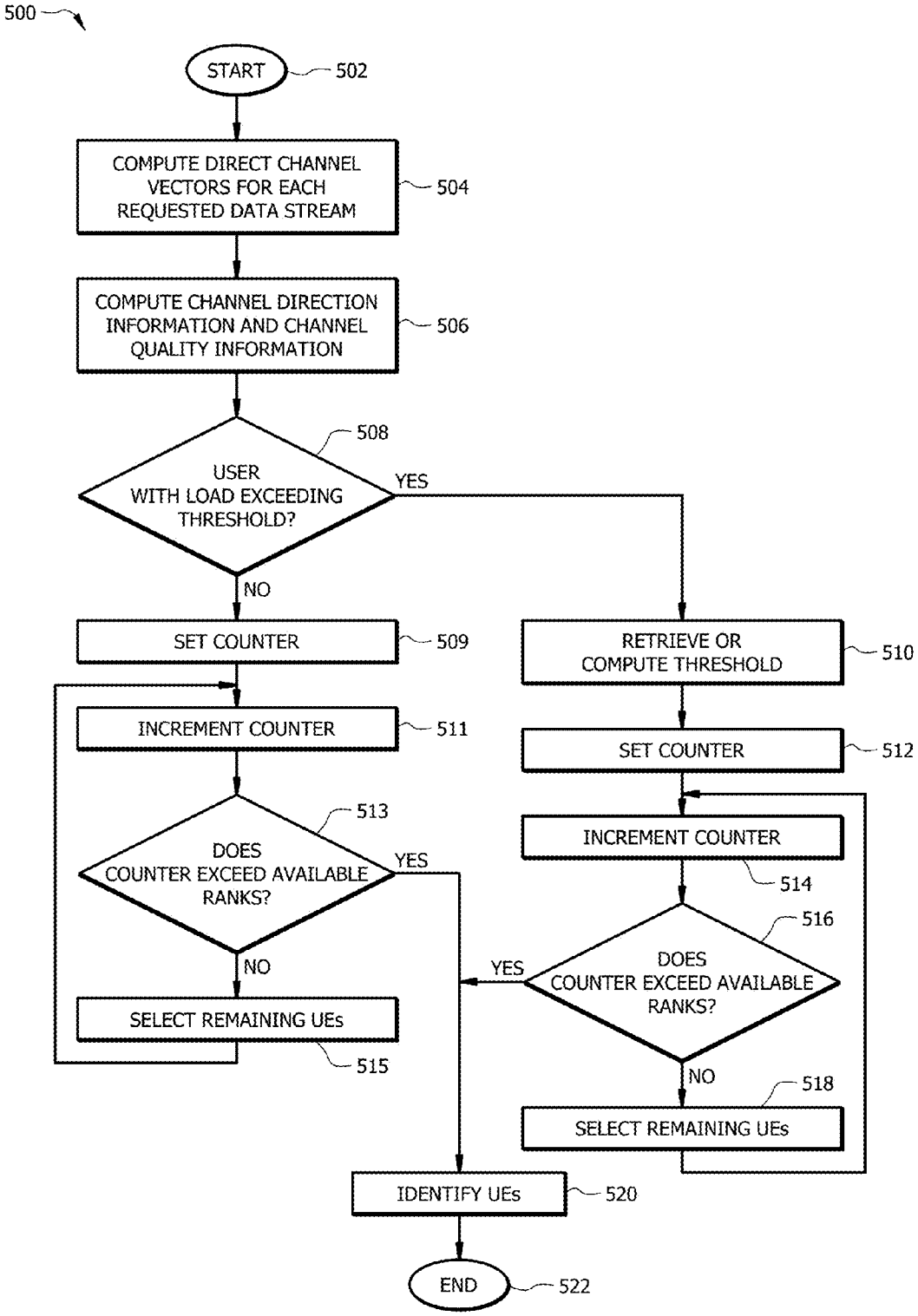
500
START
502
COMPUTE DIRECT CHANNEL VECTORS FOR EACH REQUESTED DATA STREAM
504
COMPUTE CHANNEL DIRECTION INFORMATION AND CHANNEL QUALITY INFORMATION
506
508
USER WITH LOAD EXCEEDING THRESHOLD?
YES
NO
SET COUNTER
509
INCREMENT COUNTER
511
513
DOES COUNTER EXCEED AVAILABLE RANKS?
YES
NO
SELECT REMAINING UEs
515
RETRIEVE OR COMPUTE THRESHOLD
510
SET COUNTER
512
INCREMENT COUNTER
514
516
DOES COUNTER EXCEED AVAILABLE RANKS?
YES
NO
SELECT REMAINING UEs
518
IDENTIFY UEs
520
END
522

FIG. 5

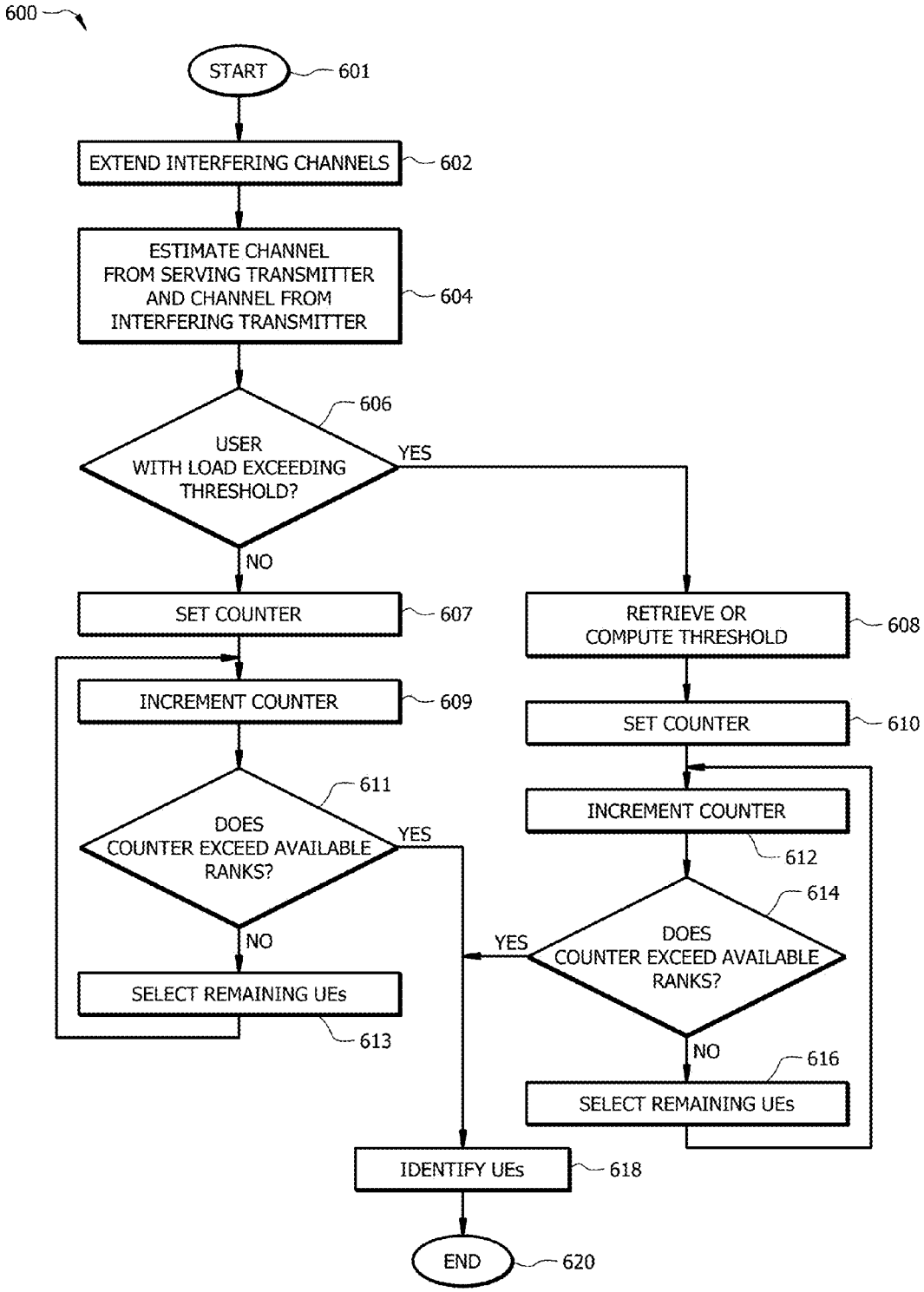
600
START
601
EXTEND INTERFERING CHANNELS
602
ESTIMATE CHANNEL FROM SERVING TRANSMITTER AND CHANNEL FROM INTERFERING TRANSMITTER
604
606
USER WITH LOAD EXCEEDING THRESHOLD?
YES
NO
SET COUNTER
607
INCREMENT COUNTER
609
611
DOES COUNTER EXCEED AVAILABLE RANKS?
YES
NO
SELECT REMAINING UEs
613
RETRIEVE OR COMPUTE THRESHOLD
608
SET COUNTER
610
INCREMENT COUNTER
612
614
DOES COUNTER EXCEED AVAILABLE RANKS?
YES
NO
SELECT REMAINING UEs
616
IDENTIFY UEs
618
END
620

FIG. 6

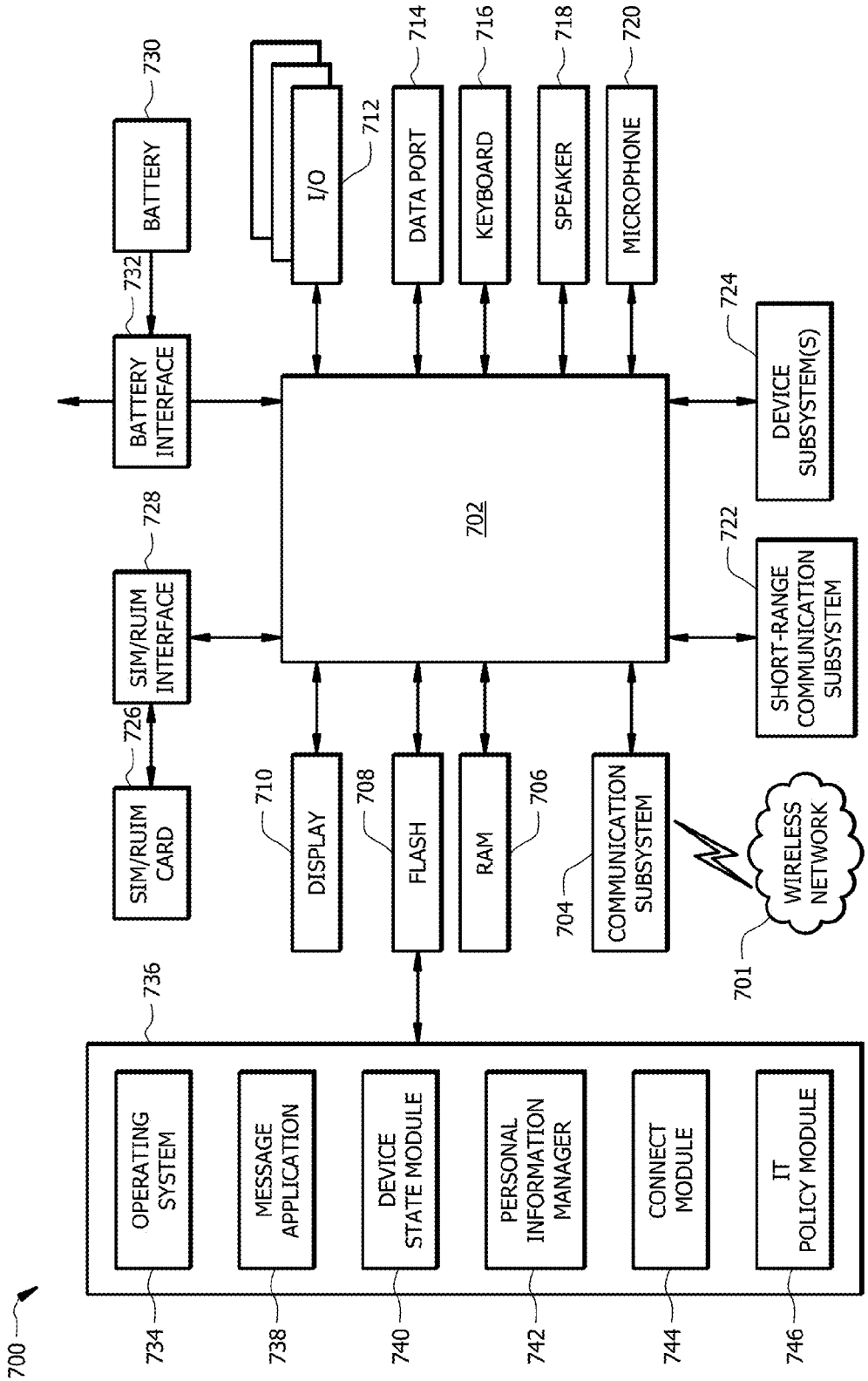
700
734
OPERATING SYSTEM
738
MESSAGE APPLICATION
740
DEVICE STATE MODULE
742
PERSONAL INFORMATION MANAGER
744
CONNECT MODULE
746
IT POLICY MODULE
736
DISPLAY
710
FLASH
708
RAM
706
COMMUNICATION SUBSYSTEM
704
WIRELESS NETWORK
701
SIM/RUIM CARD
726
SIM/RUIM INTERFACE
728
BATTERY INTERFACE
732
BATTERY
730
702
I/O
712
DATA PORT
714
KEYBOARD
716
SPEAKER
718
MICROPHONE
720
DEVICE SUBSYSTEM(S)
724
SHORT-RANGE COMMUNICATION SUBSYSTEM
722

FIG. 7

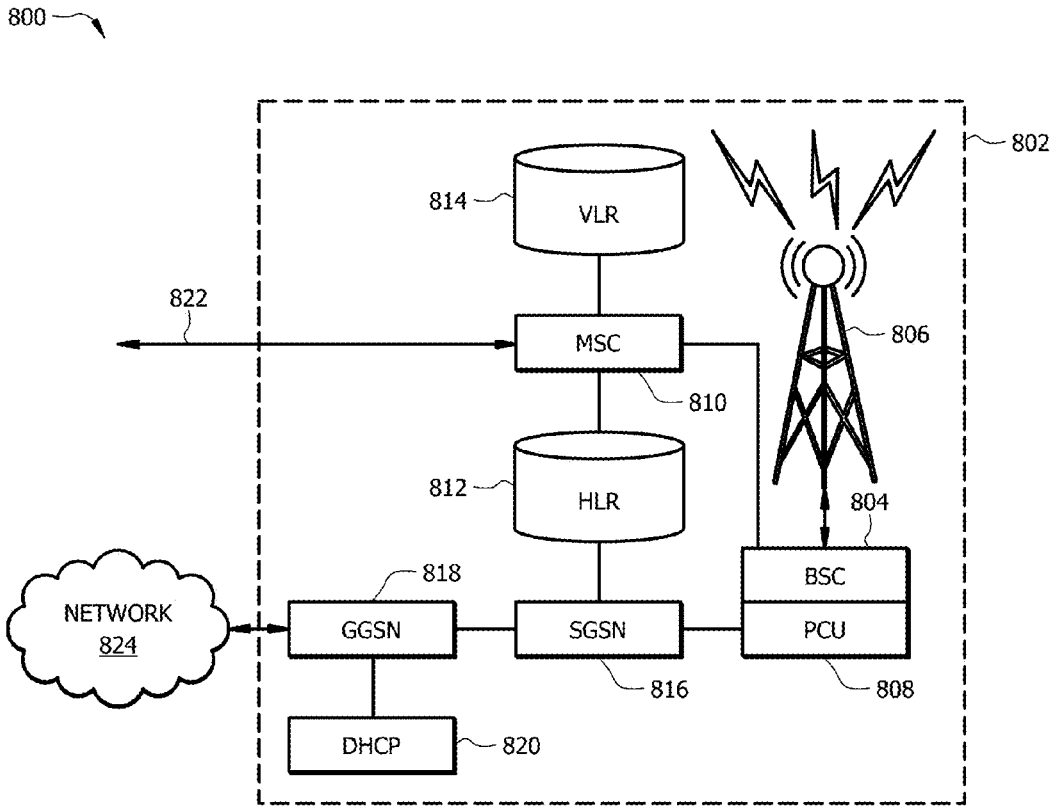
800
802
814
VLR
822
MSC
806
810
812
HLR
804
818
BSC
NETWORK
824
GGSN
SGSN
PCU
816
808
DHCP
820

FIG. 8

MIXED RANK DOWNLINK MULTI-USER INTERFERENCE ALIGNMENT SCHEME

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a U.S. National Stage of International Application No. PCT/IB2011/050427, entitled "Mixed Rank Downlink Multi-User Interference Alignment Scheme", filed Feb. 1, 2011, which is incorporated by reference in its entirety.

BACKGROUND

One of the major challenges in wireless communication systems is to overcome interference caused by other users, such as when a mobile device in cellular systems receives interfering signals from multiple transmitters. Traditional schemes attempt to manage interference as noise or by orthogonalizing channel resources between different transmitters (base stations or access points) by assigning different frequency channels, time slots, or codes to different resources (e.g., FDMA/TDMA/CDMA). In addition, concurrent transmission techniques (interference alignment (IA)) have been proposed in which multiple senders jointly encode signals to multiple receivers so that interference is aligned and each receiver is able to decode its desired information. Interference alignment provides better performance than orthogonalization-based schemes by aligning the interference at a receiver coming from different sources in the least possible spatial dimensions to maximize the number of interference-free dimensions and hence, providing more degrees of freedom for signal transmission and improving the throughput performance. With interference alignment, a transmitter can partially or completely "align" its interference with unused dimensions of the primary terminals, thereby maximizing the interference-free space for the desired signal in an interference channel. For example, it has been shown that all the interference can be concentrated roughly into one half of the signal space at each receiver, leaving the other half available to the desired signal and free of interference. When considering sum capacity for n users in the high SNR regime, the sum capacity for each transmitter scaling as n/2 log(SNR) is achievable which is equivalent to n/2 degrees of freedom for the sum capacity for each transmitter. Moreover, for fixed SNR values, the sum capacity achieved by interference alignment has been shown to scale linearly with n. Interference alignment has also been considered in a Macro-cell scenario where multiple base stations (eNBs), each serving a rank-one user equipment (UE) device, collaborate with each other to decrease the effect of interference caused to each other's transmissions.

A significant challenge with existing interference alignment schemes is that they require perfect global channel knowledge about all channels in the network, which in turn imposes significant feedback overhead and coordination between nodes. In addition, existing interference alignment schemes are highly sensitive to channel estimation and quantization error, antenna configuration, and mobility. Accordingly, a need exists for improved methods, systems and devices for managing interference between network nodes to overcome the problems in the art, such as outlined above. Further limitations and disadvantages of conventional processes and technologies will become apparent to one of skill in the art after reviewing the remainder of the present application with reference to the drawings and detailed description which follow.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure may be understood, and its numerous objects, features and advantages obtained, when the following detailed description is considered in conjunction with the following drawings, in which:

FIG. **1** is a schematic diagram showing components of a communication system in which there is downlink multi-user interference alignment between two transmitters and one or more mixed rank receivers in accordance with selected embodiments of the present disclosure;

FIG. **2** is a schematic diagram showing components of a communication system which provides interference alignment between two interfering transmitters which may each send mixed rank transmissions to the maximum possible number of receivers simultaneously while only requiring local channel state knowledge at the transmitters such that all crossed channels are aligned to a predetermined reference vector;

FIG. **3** is a flow chart illustrating an interference alignment process that may be performed when the number of receiver antennas equals or exceeds the number of transmitter antennas;

FIG. **4** is a flow chart illustrating an interference alignment process that may be performed to extend the interfering channels in frequency in cases when the number of transmitter antennas exceeds the number of receiver antennas;

FIG. **5** is a flow chart illustrating a receiver selection process that may be performed when the number of receiver antennas equals or exceeds the number of transmitter antennas;

FIG. **6** is a flow chart illustrating a receiver selection process that may be performed to extend the interfering channels in frequency in cases when the number of transmitter antennas exceeds the number of receiver antennas;

FIG. **7** is a block diagram of a user equipment device; and

FIG. **8** is a block diagram of a node of a wireless network.

DETAILED DESCRIPTION

The present disclosure is directed in general to communications systems and associated methods of operation. In one aspect, the present disclosure relates to an interference alignment scheme for use in a wireless communication system.

An embodiment is directed to a method for aligning interference at a rank d receiver having K receive antennas caused by first and second transmitters each having M transmit antennas, comprising: assembling at the receiver a first channel matrix for a first transmitter and a second channel matrix for a second transmitter, computing an equivalent direct channel matrix from the first and second channel matrices and d predetermined vectors selected from a plurality of predetermined vectors having size M, and applying a combining matrix to decode rank d data signals received at the receiver, where the combining matrix is derived from the d predetermined vectors and an inverse of the second channel matrix to project all cross channels from the second transmitter to the d predetermined vectors to reduce or eliminate interference from the second transmitter.

An embodiment is directed to a method for transmitting one or more signals from a first transmitter having M transmit antennas to one or more receivers affiliated with the first transmitter, where each of the one or more receivers has K receive antennas and receives interference from a second transmitter having M transmit antennas, comprising: acquiring at the first transmitter an equivalent direct channel matrix from each of the one or more receivers, selecting a subset of

the one or more receivers to receive a signal from the first transmitter, selecting a rank of the signal for each receiver, and for selected receivers, applying a precoding matrix to the signal to be transmitted from the first transmitter, where the precoding matrix is derived from d_{max}^{i} predetermined vectors and any equivalent direct channel matrix from selected receivers affiliated with the first transmitter to reduce or eliminate interference to any receivers receiving signals from the first transmitter or from the second transmitter.

An embodiment is directed to a user equipment device configured to receive rank d signaling over a direct channel and align interference from a cross channel, comprising: an array of K receive antennas for receiving one or more signals over a direct channel from a first transmitter having M transmit antennas and to receive one or more interfering signals over a cross channel from a second transmitter having M transmit antennas, and a processor configured to align interference from the one or more interfering signals over the cross channel by: computing a direct channel matrix for the direct channel and a cross channel matrix for the cross channel, determining a rank d of the direct channel, selecting d predetermined vectors from a set of predetermined vectors having size M, where the set of predetermined vectors is known by at least the first and second transmitters, computing a combining matrix as a product of an Hermitian of the d predetermined vectors and an inverse of the cross channel matrix, and applying the combining matrix to decode rank d data signals received at the user equipment device to project all cross channel signals from the second transmitter to an Hermitian of the d predetermined vectors to reduce or eliminate interference from the second transmitter.

An embodiment is directed to a computer-readable non-transitory storage medium embodying a computer program comprising instructions for aligning interference from a cross channel by: estimating a direct channel matrix for a direct channel from a first transmitter having M transmit antennas to a receiver having K receive antennas for receiving one or more signals over the direct channel, estimating a cross channel matrix for a cross channel from a second transmitter having M transmit antennas to the receiver having K receive antennas for receiving one or more interfering signals over the cross channel, determining a rank d of the direct channel, selecting d predetermined vectors from a set of predetermined vectors having size M, where the set of predetermined vectors is known by the first and second transmitters, computing a combining matrix as a product of an Hermitian of the d predetermined vectors and an inverse of the cross channel matrix, and applying a combining matrix to decode rank d data signals received at the receiver to project all cross channels from the second transmitter to an Hermitian of the d predetermined vectors to reduce or eliminate interference from the second transmitter.

An embodiment is directed to a method for selecting and scheduling a plurality of rank d receivers having K receive antennas to receive one or more data streams from a first transmitter having M transmit antennas while aligning interference from a second transmitter having M transmit antennas, comprising: assembling at the first transmitter a channel direction information (CDI) value and a channel quality information (CQI) value for each data stream to be sent to each of the plurality of rank d receivers, where the CDI and CQI values associated with a data stream at a rank d receiver are each derived from at least an equivalent direct channel matrix computed from one or more predetermined vectors having size M which are applied to project all cross channels from the second transmitter to the one or more predetermined vectors to reduce or eliminate interference from the second transmitter, selecting a first rank d receiver from the plurality of rank d receivers by computing a weighted CQI value for each data stream and choosing a rank d receiver having the largest weighted CQI value, and sequentially selecting one or more rank d receivers from the plurality of rank d receivers by computing a measure of orthogonality with respect to any previously selected rank d receiver that is derived from at least the CDI values and choosing a rank d receiver having the largest measure of orthogonality with respect to any previously selected rank d receiver.

A method, system and device are provided for aligning interference in a wireless network with a low-complexity scheme without requiring perfect global channel knowledge and the attendant overhead to achieve good performance between two interfering transmitters, each serving the maximum possible number of mixed rank receivers simultaneously, while only requiring local channel knowledge at nodes. In selected embodiments, the disclosed interference alignment scheme is provided for downlink (DL) multi-user, multiple input, multiple output (MU-MIMO) transmissions between two interfering transmitters in a wireless network where each transmitter only needs to know the channel knowledge for its affiliated receivers, and where each receiver only needs the channel knowledge from itself to both transmitters and may receive more than one stream of data from its affiliated transmitter. In the wireless network, two transmitters TX_1, TX_2 (e.g., Macro eNB, RN, Micro eNB, etc.) are each equipped with M antennas to serve L, receivers (e.g., user equipment (UE)) out of a total of N_i receivers, where each transmitter knows at least the effective channels to its corresponding receivers. Each receiver is equipped with K antennas and is positioned to potentially receive mixed rank signals from two interfering transmitters using the same time slot and frequency band. Each receiver in cell i may receive a mixed rank transmission from transmitter TX_i and uses an indexed list of linearly independent, predetermined vectors $V_{ref}=\{v_{ref}^{1}, \ldots, v_{ref}^{M}\}$ and channel knowledge H, G from each transmitter to i) convert the cross channel interference to a predetermined sub-space consisting of one or more vector(s) from the vector set V_{ref} to leave more interference-free sub-space for signal transmission in its affiliated transmitter, and ii) compute and feedback equivalent channel matrix information $H_{i,j}^{eq}$ to its affiliated transmitter. In operation, each receiver estimates the direct and cross channel information H, G from each transmitter, and then computes and feeds back equivalent channel matrix information $H_{i,j}^{eq}$ to its affiliated transmitter. With this information, each transmitter selects L_i receivers and constructs a transmitted signal by applying a selected precoding matrix V_i to the data symbols s_i to be transmitted where V_i includes a predetermined number of columns in the inverse of the matrix P_i. Separate example scenarios are described to cover the case where the number of receiver antennas is greater than or equal to the number of transmitter antennas (e.g. K≥M) and where the number of transmitter antennas is greater than the number of receiver antennas (e.g. K<M). In addition, low-complexity receiver scheduling algorithms are provided for improving the throughput performance and fairness.

Various illustrative embodiments of the present disclosure will now be described in detail with reference to the accompanying figures. While various details are set forth in the following description, it will be appreciated that the present disclosure may be practiced without these specific details, and that numerous implementation-specific decisions may be made to the disclosure described herein to achieve the device designer's specific goals, such as compliance with communication system limits or design-related constraints, which

will vary from one implementation to another. While such a development effort might be complex and time-consuming, it would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure. For example, selected aspects are shown in block diagram form, rather than in detail, in order to avoid limiting or obscuring the present disclosure. Some portions of the detailed descriptions provided herein are presented in terms of algorithms and instructions that operate on data that is stored in a computer memory. Such descriptions and representations are used by those skilled in the art to describe and convey the substance of their work to others skilled in the art. In general, an algorithm refers to a self-consistent sequence of steps leading to a desired result, where a "step" refers to a manipulation of physical quantities which may, though need not necessarily, take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It is common usage to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like. These and similar terms may be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that, throughout the description, discussions using terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

As used herein, the terms mobile wireless communication device and user equipment (UE) are used interchangeably to refer to wireless devices such as pagers, cellular phones, cellular smart-phones, wireless organizers, personal digital assistants, wireless Internet appliances, data communication devices, data messaging devices, computers, handheld or laptop computers, handheld wireless communication devices, wirelessly enabled notebook computers, mobile telephones, set-top boxes, network nodes, and similar devices that have wireless telecommunications capabilities. In wireless telecommunications systems, transmission equipment in a base station or access point transmits signals throughout a geographical region known as a cell. As technology has evolved, more advanced equipment has been introduced that can provide services that were not possible previously, including but not limited to enhanced node B (eNB) devices rather than a base station or other systems and devices that are more highly evolved than the equivalent equipment in a traditional wireless telecommunications system. Examples of such advanced or next generation equipment include, but are not limited to, LTE equipment or LTE-Advanced (LTE-A) equipment, and a packet-based network that uses such equipment can be referred to as an evolved packet system (EPS). As used herein, the terms access device or access point refer interchangeably to any component that can provide a UE with access to other components in a telecommunications system, including but not limited to a traditional base station or an LTE or LTE-A access device. An access point provides radio access to one or more UEs using a packet scheduler to dynamically schedule downlink traffic data packet transmissions and allocate uplink traffic data packet transmission resources among all the UEs communicating to the access device. The functions of the scheduler include, among others, dividing the available air interface capacity between UEs, deciding the transport channel to be used for each UE's packet data transmissions, and monitoring packet allocation and system load. The scheduler dynamically allocates resources for Physical Downlink Shared CHannel (PDSCH) and Physical Uplink Shared CHannel (PUSCH) data transmissions, and sends scheduling information to the UEs through a control channel.

Referring now to FIG. **1**, there is shown a schematic diagram depiction of a communication system **100** in which there is downlink multi-user interference alignment implemented for signal transmissions from transmitters **2**, **6** to receivers **3-5**, **7-9** in accordance with selected embodiments of the present disclosure. In the depicted embodiment, each of the transmitters TX_1 and TX_2 (e.g., eNBs) is equipped with M antennas and configured to transmit signals to receivers (e.g., UEs) which are each equipped with K antennas and configured to receive mixed rank signals. As will be appreciated, multiple dimensions can be generated by using subcarriers (in an OFDM system), antennas, or both, such that M=(# of subcarriers or # of time slots)×(# of Actual transmit antennas) and K=(# of subcarriers or # of time slots)×(# of Actual receive antennas). The area covered by transmitter TX_i is referred to as cell i and the jth UE in cell i is referred to as UE (i,j) where there are as many as L_i UEs (out of a total of N_i UEs) may be served by the transmitter TX_i. Each transmitter TX_i **2**, **6** denotes a data transmission device such as a fixed base station, a mobile base station, Macro eNB, Relay Node, Micro eNB, a miniature or femto base station, a relay station, and the like. Each of the receiver nodes **3-5**, **7-9** denotes a data reception device such as a relay station, a fixed terminal, a mobile terminal, user equipment and the like. In addition, the j^{th} receiver node or UE ($j=1, \ldots, L_i$) in the i^{th} cell is configured to receive a rank d_j^i transmission, thereby enabling mixed rank signaling. In the illustrated example, $UE_{1,1}$, $UE_{1,L1}$, and $UE_{2,1}$, receive rank-one transmissions, while $UE_{1,j}$, and $UE_{2,L2}$ receive rank-two transmissions, and $UE_{2,j}$, receives rank-three transmissions. To characterize the mixed rank signaling, the maximum rank in each cell is denoted by $d_{max}^i = \max_{j=1,\ldots,L_i} d_j^i$ and the total number of transmission rank for transmitter TX_i is denoted by $D^i=\Sigma_{j=1}^{L_i} d_j^i \leq \min(M, K)$.

Depending on the transmission scheme used by the transmitter TX_i and the location of the UEs, interference may occur at one or more of the receiver nodes **3-5**, **7-9**. For example, at the first receiver node **3** (denoted $UE_{1,1}$) in the first cell, a signal from the first transmitter TX_1 corresponds to a desired signal but a co-channel signal from the second transmitter TX_2 may cause interference if the second transmitter uses the same time slot and frequency band as the first transmitter. At the first receiver node $UE_{1,1}$, the desired signal from the first transmitter TX_1 arrives over direct channel $H_{1,1}$, while the interfering signal from the second transmitter TX_2 arrives over cross channel $G_{1,1}$. Similarly, interference may occur in the other receiver nodes **4-5**, **7-9** that decreases signal throughput of the network **100**. To overcome the interference between transmitters TX_1 and TX_2 and allow for mixed rank signaling to different receivers, an interference alignment scheme is proposed for downlink MIMO transmission where each transmitter only needs to know the channel state information (CSI) for its affiliated UEs, and each UE only needs to know the channel between itself and each transmitter. In selected embodiments, the proposed interference alignment scheme uses a plurality of linearly independent vectors $V_{ref}=\{V_{ref}^1, \ldots, v_{ref}^M\}$ to construct a one or more combining vectors at each of the UEs **3-5**, **7-9**, depending on the rank of the UE. Using the combining vectors, each UE ($j=1, \ldots, L_i$) projects all cross channels from an interfering transmitter to a predetermined sub-space span $\{(v_{ref}^l)^H\}$ for $l=1, \ldots, d_j^i$, thereby eliminating inter-cell interference if each transmitter sends its signal in the null space of the predetermined vectors $(v_{ref}^l)^H$ for $l=1, \ldots, d_j^i$. For example, each rank-one UE computes a combining vector from the first vector v_{ref} and the inverse of the cross channel, while a rank-two UE computes

two combining vectors from the first two vectors, V_{ref}^{1} and v_{ref}^{2} and the inverse of the cross channel, and so on. In addition, each transmitter uses channel quality information (CQI) and equivalent direct channel matrix information $H_{i,j}^{eq}$ for selected UEs to perform link adaptation and to precode data with a precoding matrix V_i to cancel out both the intra-cell and inter-cell interference. In this way, interference alignment is performed at the UEs by using the combining vector to convert the cross channel to the predetermined sub-spaces.

Interference Alignment for Case K≥M

As disclosed herein, the interference alignment schemes can be used in cases where the number of receive antennas on the UEs **3-5**, **7-9** is greater than or equal to the number of transmit antennas on the transmitters **2**, **6** (e.g. K≥M) since all cross channels $G_{i,j}$ are invertible with a probability of almost 1 in a multipath rich propagation environment. In this case, each transmitter TX_i is configured to select L_i users in the i^{th} cell (i=1,2) from a total of N_i users, where N_i is large enough to give the transmitters enough flexibility for pairing. In each cell, the total number of transmission rank for that cell plus the maximum rank of the other cell should be less than or equal to the transmitter's antenna count ($D^i+d_{max}^{3-i}\leq M$). Also, the direct channel from TX_i, i=1, 2, to the jth UE in the same cell is denoted by K×M dimensional matrix $H_{i,j}$, while the cross channel from the interfering transmitter to the same UE is denoted by K×M dimensional matrix $G_{i,j}$. The received signal at the j^{th} UE of cell i can be written as

$$y_{i,j}=H_{i,j}x_i+G_{i,j}x_{3-i}+n_{i,j}, i=1,2, \tag{1}$$

where x_i denotes the transmitted signal from TX_i, and $n_{i,j}$ is the receive noise at the jth UE in cell i. Both the direct and cross channels $H_{i,j}$ and $G_{i,j}$ can be estimated at the jth UE using any desired technique, such as downlink pilot or reference signaling.

In this case where the number of UE receive antennas meets or exceeds the number of transmit antennas (K≥M), all cross channels $G_{i,j}$ are invertible with a probability of almost one in a multipath rich wireless propagation environment, meaning that the pseudo inverse of the cross channel is given by $G_{i,j}^{+}=(G_{i,j}^{H}G_{i,j})^{-1}G_{i,j}^{H}$, such that $G_{i,j}^{+}G_{i,j}=I$ where I denotes the identity matrix. As a result, the interfering cross channels can be projected to a predetermined vector of size M, v_{ref}, in the case of single rank transmission by having each UE compute a combining vector $r_{i,j}=v_{ref}^{H}G_{i,j}$ and feed back an equivalent direct transmission channel vector $h_{i,j}^{eq}=v_{ref}^{H}G_{i,j}^{+}H_{i,j}$. However, to account for mixed rank signaling, each of the UEs and transmitters stores an "indexed" list of linearly independent vectors $V_{ref}=\{v_{ref}^{1}, \ldots, v_{ref}^{M}\}$, where v_{ref}^{l} is an M×1 vector. In some embodiments, V_{ref} consists of orthogonal vectors. Alternatively, V_{ref} can be considered as a set of basis vectors for the M-dimensional transmission space. While the indexed list of V_{ref} may be predefined and known to all UEs and both transmitters, it is also contemplated that each cell may have a different set of V_{ref} vectors or there could be multiple sets of V_{ref} vectors which would allow the transmitters to select or negotiate the vector that is better for their service and signal to all UEs (and probably the other transmitter). However, by using the same vector sets in both cells, system operation is simplified by eliminating any requirement of exchanging or signaling different vector sets between cells.

If the signal received at each $UE_{i,j}$ (Equation (1)) is multiplied by combining vector $r_{i,j}^{l}=(v_{ref}^{l})^{H}G_{i,j}^{+}$ for l=1, . . . , d_j^i, the result is:

$$\tilde{y}_{i,j}^{l}=(v_{ref}^{l})^{H}G_{i,j}^{+}y_{i,j}=h_{i,j}^{l,eq}x_i+(v_{ref}^{l})^{H}x_{3-i}+n_{i,j}^{i,eq}, i=1,2 \quad j=1,\ldots,L_i \tag{2}$$

where equivalent direct transmission channel matrix $h_{i,j}^{l,eq}=(v_{ref}^{l})^{H}G_{i,j}^{+}H_{i,j}$, where equivalent noise term $n_{i,j}^{l,eq}=(V_{ref}^{l})^{H}G_{i,j}^{+}n_{i,j}$, and where x_{3-i} refers to interfering data from the "other" transmitter. Thus, Equation (2) represents matching filter equations for d_j^i independent or orthogonal vectors v_{ref}^{l}.

Since the j^{th} UE at cell i requires a transmission of rank d_j^i, the indexed vector set V_{ref} must have at least d_j^i independent vectors v_{ref}^{l} to achieve a multiplexing gain of d_j^i. Considering Equation (2) for all i=1,2; j=1, . . . , L_i; l=1, . . . , d_j^i, the transmitted signal x_{3-i} (for i=1,2) should be designed such that it is in the null space of the first d_{max}^{i} vectors in the set V_{ref} in order to cancel the inter-cell interference. By satisfying this constraint in designing the transmit signal x_i and the matched filters of $(v_{ref}^{l})^{H}G_{i,j}^{+}$, in the i^{th} cell (i=1,2), for the j^{th} UE (j=1, . . . , L_i), the received signal appears as:

$$\tilde{y}_{i,j}^{l}=h_{i,j}^{l,eq}x_i+n_{i,j}^{l,eq}, l=1,\ldots,d_j^i \tag{3}$$

As seen from Equation (3), all interference from the its transmitter to the j^{th} UE in the other cell ($3-i^{th}$ cell) is aligned such that each UE in $(3-i)^{th}$ cell can decode a signal of rank d_j^{3-i}. On the other hand, the i^{th} transmitter should provide total D^i degrees of freedom for its own users. This requires that the i^{th} transmitter should have at least $D^i+d_{max}^{3-i}$ antennas.

With this scheme, in each cell, the problem is reduced to DL MU-MIMO with the equivalent channel

$$H_{i,j}^{eq}=\left[h_{i,j}^{1,eq^T}\ \ldots\ h_{i,j}^{d_j^i,eq^T}\right]^T \tag{4}$$

where $h_{i,j}^{l,eq}=(v_{ref}^{l})^{H}G_{i,j}^{+}H_{i,j}$ for the j^{th} UE (j=1, . . . , L_i) with d_{max}^{3-i} dimensions reserved for interference alignment. As a result, each UE (i,j) estimates $H_{i,j}$ and $G_{i,j}$, and then feeds back the equivalent direct transmission channel matrix $H_{i,j}^{eq}$ to its affiliated transmitter TX_i, either directly or with an indication of the matrix or of its vectors using code-book based or non-code-book based techniques. Alternatively, each transmitter TX_i operating in time division duplexing (TDD) mode can estimate $H_{i,j}^{eq}$ from the uplink channel if the $UE_{i,j}$ sends multiple pilot signals in the direction of the transpose of the combining vector $(r_{i,j}^{l})^{T}$, where $(.)^{T}$ denotes the transpose operation.

Once the transmitter TX_i acquires the equivalent direct transmission channel matrix $H_{i,j}^{eq}$ from all affiliated UEs, transmitter TX_i selects L_i UEs indexed by $(s_1, \ldots, s_{L_i})$ and constructs the transmitted signal x_i using any desired DL-MU-MIMO technique, such as zero-forcing or dirty paper coding (DPC).

In an illustrative example where zero-forcing precoding is used, the i^{th} transmitter may be configured to use the first D^i vectors in the inverse of the matrix of dimension $(D^i+d_{max}^{3-i})\times M$

$$P_i=\begin{bmatrix} H_{i,1}^{eq} \\ \vdots \\ H_{i,L_i}^{eq} \\ v_{ref}^{1^T} \\ \vdots \\ v_{ref}^{d_{max}^{3-i}T} \end{bmatrix} \tag{5}$$

as the precoding matrix V_i for constructing the transmitted signal x_i(for i=1,2). In this example, the vectors in precoding matrix V_i may be normalized so each stream has the same transmit power. As a result, the constructed transmit signal is:

$$x_i=V_i s_i \tag{6}$$

In Equation (6), $V_i=[v_{i,1}, \ldots, v_{i,L_i}]$ is the first D^i columns of the matrix $P_i^+=P_i^H(P_iP_i^H)^{-1}$, where $v_{i,j}$ is the precoding matrix of size $M\times d_j^i$ for the j^{th} user and we denote the l^{th} column ($l=1, \ldots, d_j^i$) of this matrix by $v_{i,j}^l$. In addition, $s_i=[s_{i,1} \ldots s_{i,L_i}]$ represents data symbols to be transmitted at the i^{th} transmitter and $s_{i,j}$ is a vector of size $d_j^i\times 1$ representing a rank-d_j^i signal that should be transmitted to user j. With this precoding scheme, inter-cell and intra-cell interference are cancelled and the j^{th} UE ($j=1, \ldots, L_i$) in the i^{th} cell ($i=1,2$) can decode its l^{th} data stream ($l=1, \ldots, d_j^i$) using single-user detection algorithms using

$$\hat{y}_{i,j}^l=h_{i,j}^{l,eq}v_{i,j}^l s_{i,j}^l+n_{i,j}^{l,eq}, \quad (7)$$

where $s_{i,j}^l$ denotes the l^{th} data stream sent to the UE (i,j) and $h_{i,j}^{l,eq}v_{i,j}^l$ can be considered as the equivalent channel for the l^{th} stream of j^{th} UE from the i^{th} transmitter. Each UE can calculate the required equivalent channels using reference signals, for example like 3GPP Release 8 LTE or the choice of precoding matrix/vector can be signaled to the UE.

The interference alignment schemes disclosed herein may be considered as an improved MU-MIMO technique. Some feedback schemes that exist for MU-MIMO scenarios can be used here. For example, in addition to feeding back equivalent direct channel matrix information $H_{i,j}^{eq}$, each $UE_{i,j}$ may feed back additional information to its affiliated transmitter, such as LTE Release 8 Channel Quality Indicator (CQI), or redefined CQI for MU-MIMO in LTE-A, which is used by the transmitter TX_i for scheduling and link adaptation. One example would be to have each UE feed back a threshold, such as the effective noise power, i.e., $E\{\|n_{i,j}^{eq}\|^2\}$ where

$$n_{i,j}^{eq}=\left[n_{i,j}^{1,eq} \ \ldots \ n_{i,j}^{d_j^i,eq}\right]$$

and $E\{.\}$ denotes the expectation, or its inverse

$$\frac{1}{E\{\|n_{i,j}^{eq}\|^2\}}.$$

Also, in the i^{th} cell ($i=1,2$), rank indicator (RI) information (or equivalently d_j^i) can be estimated and reported back to the transmitter by UE $j=1, \ldots, L_i$. Therefore, according to RI, each UE could send multiple CQIs for each one of RI data streams based on the effective received SNR. With this information, transmitters can perform scheduling, pairing, and link adaptation for the selected UEs by calculating the effective SNR for each one of RI data streams which can be calculate for example as

$$SNR_{i,j}^l=\frac{P_i\left\|h_{i,j}^{l,eq}v_{i,j}^l\right\|^2}{D^iE\left\{\left|n_{i,j}^{l,eq}\right|^2\right\}}.$$

In support of UE scheduling, each UE can measure and estimate the direct channel to the serving transmitter. Using the same procedure as 3GPP LTE release 8 or 10, each UE determines the rank of the channel, d_j^i. This rank determines that the UE can receive a signal up to rank d_j^i from transmitter i. Each UE can also report back d_j^i as RI information and multiple CQI for each one of d_j^i data streams. As part of scheduling operations, each transmitter selects different UEs with rank d_j^i. Transmitter i can also assign d_j^i to UE j. It could assign this value considering other UEs in the cell and UE's transmission status.

According to CQI and RI (equivalently d_j^i) for different users, the i^{th} transmitter can schedule users such that the number of transmit antennas is not less than the sum of data streams provided to the users in the i^{th} cell and the reserved data ranks for interference, i.e. $M\geq D^i+d_{max}^{3-i}$, where D^i is the degrees of freedom that the i^{th} transmitter provides for its users. Note that in this case each transmitter should know the maximum rank that the other transmitter is providing to its users (i.e. d_{max}^{3-i}). This information can be exchanged between transmitters or there can be a pre-defined setting that transmitters follow. In one embodiment, they can agree on a pre-defined value, i.e. $d_{max}^1=d_{max}^2$.

It is favorable that this scheme is implemented for the case that all UEs in each cell request a fixed rank, i.e. $d_j^i=d^i$ for $j=1, \ldots, L_i$. For example, the first transmitter schedules those users that all request a rank-**1** data stream and the second transmitter schedules those users that all request a rank-**2** data stream. In this way, if all UEs in a cell request rank-one data streams except one which requests a rank-**2** data stream, the other transmitter should reserve two dimensions for a rank-**2** interference. This can be considered as a waste of resources which can be addressed during UE scheduling.

By using the combining vector $r_{i,j}^l=(v_{ref}^l)^HG_{i,j}^+$ for $l=1, \ldots, d_j^i$ at each UE to project all interfering cross channels to the respective predetermined subspace span $\{(v_{ref}^l)^H\}$, the disclosed interference alignment scheme allows a UE to decode a plurality of data streams sent by an affiliated transmitter using the combining vector $r_{i,j}^l$ which decodes the precoding matrix V_i (from Equation (6)).

To understand how a plurality of linearly independent reference vectors $(v_{ref}^l)^H$ may be used to align interference in the network **100**, reference is now made to FIG. **2** which schematically depicts a communication system **200** which provides interference alignment between two interfering access devices **20**, **30** and one or more mixed rank user equipment (UE) devices **10-12** requiring only local channel state knowledge at the access devices **20**, **30** such that all crossed channels are aligned to the predetermined reference sub-spaces. To this end, each of the UEs **10-12** is configured to compute equivalent direct channel matrix information $H_{i,j}^{eq}$ from a plurality of linearly independent reference vectors $(v_{ref}^l)^H$. After feeding back the equivalent direct channel matrix information $H_{i,j}^{eq}$ to the affiliated access device (e.g., **20**), the access device **20** constructs a transmission signal x by precoding the transmit data in the null space of $(v_{ref}^l)^H$ so that no interference is imposed to the UEs in the other cell. For purposes of transforming the transmit data and signals as described herein, the UE **10** includes, among other components, one or more processors **110** that run one or more software programs or modules embodied in circuitry and/or non-transitory storage media device(s) **111** (e.g., RAM, ROM, flash memory, etc.) to communicate with access device **20** to receive data from, and to provide data to, access device **20**. When data is transmitted from UE **10** to access device **20**, the data is referred to as uplink data and when data is transmitted from access device **20** to UE **10**, the data is referred to as downlink data.

As part of the MIMO downlink process, the UE **10** determines, quantifies or estimates the channel matrices H and G which respectively represent the channel gain between the first access device **20** and second access device **30** and the UE. For example, the channel matrix H can be represented by a $K\times M$ matrix of complex coefficients, where M is the number of transmit antennas in the first access device **20** and K is the

number of receive antennas in the UE **10**. Alternatively, the channel matrix H can instead be represented by an M×K matrix of complex coefficients, in which case the matrix manipulation algorithms are adjusted accordingly. The coefficients of the channel matrix H depend, at least in part, on the transmission characteristics of the medium, such as air, through which a signal is transmitted. A variety of methods may be used at the receiver to determine the channel matrix H and G coefficients, such as transmitting a known pilot signal to a receiver so that the receiver, knowing the pilot signal, can estimate the coefficients of the channel matrix H and G using well-known pilot estimation techniques. Alternatively, when the channel between the transmitter and receiver are reciprocal in both directions, the actual channel matrix H is known to the receiver and may also be known to the transmitter. To this end, each access device (e.g., **20**) may include a pilot signal generator (e.g., **212**) for generating and transmitting a pilot signal **213**. In addition, each UE **10** may include a channel estimation module **112** using hardware and/or software executed by one or more processor elements to determine or estimate the channel matrices H and G from the access devices **20**, **30**.

At the UE **10**, a combining vector computation module **114** is provided for computing or retrieving a combining vector $r_{i,j}^{l}$. In the cases where the UE antenna count K is at least equal to the access device antenna count M, the estimated channel matrices H and G may be used to compute the combining vector by first computing the pseudo inverse of the interfering cross channel G^{+}. Next, an arbitrary set of linearly independent reference vectors $V_{ref}=\{v_{ref}^{1}, \ldots, v_{ref}^{M}\}$, each of size M, is defined or obtained, where the reference vector set V_{ref} is known to all UEs and transmitters because it was signaled or pre-determined. In one embodiment, V_{ref} consists of orthogonal reference vectors. Assuming a signal of rank-d should be received by UE **10**, after determining the Hermitian transpose of d reference vectors from the reference vector set, $(v_{ref}^{l})^{H}$ for l=1, . . . , d, the computation module **114** then computes the combining vector $r^{l}=(v_{ref}^{l})^{H}G^{+}$.

The UE **10** also includes an equivalent channel matrix computation module **116** which multiplies the combining vector r^{l} and estimated direct channel matrix H to compute the equivalent channel matrix $H_{i,j}^{eq}$ where its l^{th} row (the equivalent channel matrix for each data stream) is calculated by $h_{i,j}^{l,eq}=r^{l}H=(v_{ref}^{l})^{H}G^{+}H$. The UE **10** may feed back the equivalent channel matrix $H_{i,j}^{eq}$ a to the access point **20**, which also receives equivalent channel matrix information from the other affiliated UEs **11**, **12** in the cell for access point **20**. In selected embodiments, the feedback module **118** sends the equivalent channel matrix $H_{i,j}^{eq}$ as an uplink message **119**. Alternatively, when TDD mode is used, the access point **20** can estimate the equivalent channel matrix $H_{i,j}^{eq}$ a from the uplink channel if the UE sends the multiple pilot signals in the direction of $(r^{l})^{T}$. The feedback module **118** may also send RI and multiple CQI information, such as an indication of effective noise power, to the access point **20** for use in scheduling and link adaptation.

At the access device **20**, the equivalent channel matrix $H_{i,j}^{eq}$ and RI/CQI information is processed and transformed by one or more processors **210** that run one or more software programs embodied in non-transitory storage media device(s) **211** (e.g., RAM, ROM, flash memory, etc.). For example, after receiving the equivalent channel matrix $H_{i,j}^{eq}$ and ad any RI or CQI information from all affiliated UEs **10-12**, the access point **20** processes the feedback information to avoid any co-channel interference to non-affiliated UEs. To this end, a selection module **214** at the access point **20** uses the acquired equivalent channel matrices and any RI or CQI information to select a subset of L_i UEs out of a total of N_i UEs. The selected L_i UEs are indexed by $(s_1, \ldots, s_{L_i})$. In addition, the access device **20** includes a precoding module **216** which uses the equivalent channel matrices to construct or precode a transmit signal $x_i=V_i s_i$, where V_i denotes the precoding matrix for the ith transmitter or access device and s_i represents data symbols to be transmitted at the ith transmitter or access device. In particular, the precoding module **216** may compute the precoding matrix V_i by computing matrix P, computing the inverse matrix P^{+}, and then selecting the first D^{i} columns of the matrix P^{+}, where D^{i} is the total number of transmission rank $(D^{i}=\Sigma_{j=1}^{L_i} d_j^{i} \leq \min(M, K))$. Assuming zero-forcing precoding, the access device **20** may be configured as the ith transmitter to compute matrix P of dimension $(D^{i}+d_{max}^{3-i})\times M$, as

$$P_i = \begin{bmatrix} H_{i,1}^{eq} \\ \vdots \\ H_{i,L_i}^{eq} \\ v_{ref}^{1^T} \\ \vdots \\ v_{ref}^{d_{max}^{3-i}T} \end{bmatrix},$$

followed by computation of the inverse matrix $P_i^{+}=P_i^{H}(P_i P_i^{H})^{-1}$, followed by the selection of the first D^{i} columns of matrix P_i^{+} to form the precoding matrix $V_i=[v_{i,1} \ldots v_{i,L_i}]$, where $v_{i,j}$ is the precoding matrix of size $M\times d_j^{i}$ for the j^{th} user with the l^{th} column $(l=1, \ldots, d_j^{i})$ of this matrix denoted by $v_{i,j}^{l}$. Though not shown, there may also be scheduling and link adaptation performed on the data symbols s_i at the precoding module **216** or transmit module **218**. As the precoded data x_i is transmitted over a downlink message **219** to the UE **10**, it is received at the decode module **120** where it appears as the received signal $\tilde{y}_{i,j}^{l}=h_{i,j}^{l,eq}v_{i,j}^{l}s_{i,j}^{l}+n_{i,j}^{l,eq}$ in which the inter-cell and intra-cell interference are cancelled. As a result, the UE **20** can decode data from the received signal $\tilde{y}_{i,j}^{l}$ using single user detection algorithms.

Referring now to FIG. **3**, there is depicted in flow chart form an interference alignment process **300** that may be performed when the number of receiver antennas K equals or exceeds the number of transmitter antennas M. Once the procedure starts (step **302**), each $UE_{i,j}$ device estimates or computes at (step **304**) the direct channel $H_{i,j}$ and cross channel $G_{i,j}$ to the $UE_{i,j}$ device from potentially interfering transmitters TX_1 and TX_2. Channel information may be computed using pilot estimation techniques.

At step **306**, each $UE_{i,j}$ device computes the combining vectors $r_{i,j}^{l}$ for each stream based on the cross channel $G_{i,j}$, such as by multiplying the Hermitian reflection of the shared reference vectors v_{ref}^{l} (for l=1, . . . , d_j^{i}) and the pseudo inverse of the cross channel $G_{i,j}^{+}$. In addition, each $UE_{i,j}$ device computes the equivalent direct channel matrix information $H_{i,j}^{eq}$ based on the estimated direct channel $H_{i,j}$ and the computed combining vectors $r_{i,j}^{l}$.

At step **308**, each transmitter TX_i acquires (e.g., by feedback) the equivalent direct channel matrix information

$$H_{i,j}^{eq} = \left[h_{i,j}^{1,eq^T} \ \ldots \ h_{i,j}^{d_j^{i},eq^T} \right]^T$$

for the affiliated UE devices, along with any channel quality indicator (CQI), either directly or indirectly using codebook or non-codebook techniques.

At step **310**, each transmitter TX_i selects L_i UE devices from a total of N_i UE devices in the ith cell, and then constructs transmit signals x_i for the selected UEs. In selected embodiments, the transmit signals x_i are constructed using a precoding matrix technique (such as described at Equations (5) and (6)) and/or link adaptation technique (such as described herein)), and then transmitted as downlink data to the selected UEs.

At step **312**, each $UE_{i,j}$ device decodes its transmitted signal x_i which appears as a receive signal vector $\tilde{y}_{i,j}^{\ l}=h_{i,j}^{\ l,eq}v_{i,j}^{\ l}s_{i,j}^{\ l}+n_{i,j}^{\ l,eq}$. In order to decode the receive signal vector, each $UE_{i,j}$ device may know or derive its own precoding vectors $v_{i,j}^{\ l}$. At step **314**, the process ends.

Interference Alignment for Case K<M

In addition to the foregoing, selected embodiments may also implement the disclosed interference alignment schemes in cases where the number of antennas on the eNB is greater than the number of receive antennas on the UE (e.g. K<M), provided that adjustments are made to match or correlate the cross channels $G_{i,j}$ with the predetermined vectors $(v_{ref}^{\ l})^H$. The adjustments are required because the cross channels $G_{i,j}$ are not invertible in the case where the UE antenna count K is less than the access device antenna count M, and as a result, combining vectors $r_{i,j}^{\ l}$ (described above) cannot be used to match the equivalent cross channels perfectly to the predetermined vectors $(v_{ref}^{\ l})^H$. To address this matching problem, a number of adjustment schemes may be used.

Euclidean Distance Minimization

In a first adjustment scheme, Euclidean Distance Minimization (EDM) techniques may be used to find or compute an EDM combining vector $r_{i,j}^{\ l}$ which minimizes the Euclidean distance of the equivalent interference channels for the l^{th} data stream of each UE to $(v_{ref}^{\ l})^H$. Referring to FIG. **2**, the EDM technique may be implemented by the combining vector computation module **114** at each UE to compute the combining vector for the l^{th} data stream as follows:

$$r_{i,j}^{l}=\frac{(v_{ref}^{l})^{H}G_{i,j}^{+}}{\left\|(v_{ref}^{l})^{H}G_{i,j}^{+}G_{i,j}\right\|},\ l=1,\ldots,d_j^i. \tag{8}$$

where $G_{i,j}^{+}=G_{i,j}^{H}(G_{i,j}G_{i,j}^{H})^{-1}$ such that $G_{i,j}^{+}$ is defined such that $G_{i,j}G_{i,j}^{+}=I$.

Once the EDM combining vector $r_{i,j}^{\ l}$ is computed, the equivalent direct channel matrix for each stream is computed as follows:

$$h_{i,j}^{l,eq}=\frac{(v_{ref}^{l})^{H}G_{i,j}^{+}H_{i,j}}{\left\|(v_{ref}^{l})^{H}G_{i,j}^{+}G_{i,j}\right\|},\ l=1,\ldots,d_j^i. \tag{9}$$

The remaining processing at the UE **10** and access point **20** proceeds substantially as described with reference to steps **308-314** in the interference alignment process **300** depicted in FIG. **3** except the fact that the calculation of CQI will be affected by the amount of inter-cell interference since the inter-cell interference cannot be cancelled completely. As a result, the computation of effective SNR at the transmitter for scheduling and link adaptation may be replaced by computing an effective signal to interference plus noise ratio (SINR) as follows:

$$SINR_{i,j}^{l,eff}=\frac{\frac{P_i}{D^i}\left\|h_{i,j}^{l,eq}v_{i,j}^{l}\right\|^2}{\frac{P_{3-i}}{M-1}\left(1-\left|r_{i,j}^{l}G_{i,j}v_{ref}^{l}\right|^2\right)+E\left\{\left|n_{i,j}^{l,eq}\right|^2\right\}}, \tag{10}$$

where P_{3-i} refers to interfering power from the "other" transmitter, $h_{i,j}^{\ l,eq}$ is defined in Equation (9), $r_{i,j}^{\ l}$ is obtained as in Equation (8), and $v_{i,j}^{\ l}$ is the precoding vector for the l^{th} data stream of the UE (i,j). As a result of this adjustment, the CQI computation at the can be modified to capture the inter-cell interference term

$$\frac{P_{3-i}}{M-1}\left(1-\left|r_{i,j}^{l}G_{i,j}v_{ref}^{l}\right|^2\right).$$

Time/Frequency Extension

In a second adjustment scheme for cases where the number of antennas on the eNB is greater than the number of receive antennas on the UE (e.g. K<M), the interfering channels of UEs are extended in time or frequency domain such that the aggregate channel becomes invertible. For example, in OFDM systems like LTE or LTE-Advanced systems, the channels can be extended by using time/frequency resource elements. By extending the time/frequency of the interfering co-channels, the combining vector $r_{i,j}^{\ l}$ can be used to match the extended cross channels $G_{i,j}$ with the to the predetermined vectors $(v_{ref}^{\ l})^H$.

To illustrate an example interference alignment process that may be performed to extend the interfering channels in frequency, reference is now made to FIG. **4** which depicts in flow chart form an interference alignment process **400** that may be performed in cases when the number of transmitter antennas M exceeds the number of receiver antennas K. Once the procedure starts (step **402**), each $UE_{i,j}$ device effectively extends the interfering channels by finding or deriving n**1** and n**2** (at step **404**) that are the smallest integer numbers such that:

$$n1M=n2K(n2>n1). \tag{11}$$

For example, if M=4 and K=2, then we have n**1**=1 and n**2**=2.

At step **406**, each $UE_{i,j}$ device estimates or computes the direct channel $H_{i,j}$ and cross channel $G_{i,j}$ in each of the subcarriers w_1 to w_{n2} of the channels between the $UE_{i,j}$ device and potentially interfering transmitters TX_1 and TX_2. The channel estimation module **112** shown in FIG. **2** may be used here to implement pilot signal estimation or any other desired channel estimation technique.

At step **408**, each $UE_{i,j}$ device computes extended direct and cross channel matrix information. The combining vector computation module **114** shown in FIG. **2** may be used to compute the extended direct and cross channel matrix information. To implement frequency extension, the cross channel of the UE (i,j) in the subcarriers w_1 to w_{n2} may be denoted as $\{G_{i,j}(w_k)\}_{k=1}^{n_2}$, where it is understood that a subcarrier refers to a frequency unit or band. With this approach, the aggregate cross channel is defined as

$$G_{i,j}\triangleq[G_{i,j}(w_1)^T|\ldots|G_{i,j}(w_{n_2})^T]^T. \tag{12}$$

where $[.]^T$ denotes the transpose operation. From the foregoing, the size of the cross channel $G_{i,j}$ is therefore $(Kn_2)\times M=(Mn_1)\times M$, and the cross channel $G_{i,j}$ may be represented as follows:

$$G_{i,j}=[F_{i,j}(t_1)^T|\ldots|F_{i,j}(t_{n_1})^T]^T, \tag{13}$$

in which $(F_{i,j}(t_k)_{k=1}^{n}$ are all square M×M matrices that are invertible with probability almost equal to one in a multipath rich frequency selective channel with tone separations larger than the coherence channel bandwidth. Similarly, the aggregate matrix of direct channels

$$H_{i,j} \triangleq [H_{i,j}(w_1)^T|\ldots|H_{i,j}(w_{n_2})^T]^T$$

may be represented as:

$$H_{i,j}=[K_{i,j}(t_1)^T|\ldots|K_{i,j}(t_{n_1})^T]^T \quad (14)$$

With this transformation, the transmitted and received signals and noise vectors in the subcarriers $w_1, \ldots, w_{n2}$ can be transformed to:

$$x_i \triangleq [x_i(w_1)^T|\ldots|x_i(w_{n_2})^T]^T = [q_i(t_1)^T|\ldots|q_i(t_{n_1})^T]^T, \quad (15)$$

$$y_{i,j} \triangleq [y_{i,j}(w_1)^T|\ldots|y_{i,j}(w_{n_2})^T]^T = [z_{i,j}(t_1)^T|\ldots|z_{i,j}(t_{n_1})^T]^T, \quad (16)$$

$$n_{i,j} \triangleq [n_{i,j}(w_1)^T|\ldots|n_{i,j}(w_{n_2})^T]^T = [w_{i,j}(t_1)^T|\ldots|w_{i,j}(t_{n_1})^T]^T. \quad (17)$$

To conclude step **408**, each $UE_{i,j}$ device computes the interference channel matrix $F_{i,j}(t_k)$ (from Equation (13)) and direct channel matrix $K_{i,j}(t_k)$ (from Equation (14))

At step **410**, each $UE_{i,j}$ device computes the equivalent direct channel vector $k_{i,j}^{l,eq}(t_k)$ for each t_k, k=1, . . . n**1** based on the direct channel matrix $K_{i,j}(t_k)$ for each data stream l=1, . . . , d_j^i assigned/requested for UE. In an example embodiment, each $UE_{i,j}$ device computes the equivalent direct channel vector $k_{i,j}^{l,eq}(t_k)$ by first computing or deriving a combining vectors $r_{i,j}^{l}(t_k)=(v_{ref}^{l})^H F_{i,j}^{-1}(t_k)$, such as by multiplying the Hermitian of the shared predetermined reference vector v_{ref}^{l} and the inverse of the effective cross channel $F_{i,j}^{-1}(t_k)$. By multiplying the predetermined reference vector(s) v_{ref}^{l} and the direct channel matrix $K_{i,j}(t_k)$, each $UE_{i,j}$ device then computes the equivalent direct channel matrix

$$k_{i,j}^{l,eq}(t_k) \triangleq (v_{ref}^{l})^H F_{i,j}^{-1}(t_k) K_{i,j}(t_k),$$

and computes

$$w_{i,j}^{l,eq}(t_k) \triangleq (v_{ref}^{l})^H F_{i,j}^{-1}(t_k) w_{i,j}(t_k).$$

The equivalent channel vector computation module **116** shown in FIG. **2** may be used to compute the equivalent channel matrix $K_{i,j}^{eq}(t_k)$.

At this point, the equivalent direct channel matrix $K_{i,j}^{eq}(t_k)$ may be fed back to its affiliated access device along with any channel quality indicator (CQI), either directly or indirectly using codebook or non-codebook techniques. The feedback module **118** shown in FIG. **2** may be used to feedback the effective channel vector and CQI information. In addition or in the alternative, each of the transmitters TX_1 and TX_2 may acquire the equivalent direct channel matrix $K_{i,j}^{eq}(t_k)$ using uplink channel estimation techniques.

At step **412**, each transmitter TX_i acquires $\{k_{i,j}^{l,eq}(t_k)\}_{k=1}^{n1}$ and $\{CQI_{i,j}^{l}(t^k)\}_{k=1}^{n1}$ (possibly via the feedback information by UEs) for its affiliated UEs, and uses this information to select L_i UE devices from a total of N_i UE devices in the ith cell. The selection module **214** shown in FIG. **2** may be used to select the L_i UE devices indexed by $(s_1, \ldots, s_{Li})$ based on the received effective channel vector and RI/CQI information. With this information, each transmitter TX_i computes the equivalent direct channel $K_{i,j}^{eq}(t_k)$ as:

$$K_{i,j}^{eq}(t_k) = \left[k_{i,j}^{1,eq}(t_k)^T \ \ldots \ k_{i,j}^{d_j^i,eq}(t_k)^T\right]^T, \quad (18)$$

In addition, each transmitter TX_i computes the aggregate matrix $B_i(t_k)$ as:

$$B_i(t_k) \triangleq \left[K_{i,1}^{eq}(t_k)^T \ldots K_{i,L_i}^{eq}(t_k)^T v_{ref}^{1} \ldots v_{ref}^{d_{max}^{3-i}}\right]^T. \quad (19)$$

At step **412**, each transmitter TX_i also constructs transmit signals $\{q_i(t_k)\}_{k=1}^{n1}$ for the selected L_i UE devices. In selected embodiments, the precoding module **216** shown in FIG. **2** may be used to the construct transmit signals $q_i(t_k)$ using a precoding matrix $V_i(t_k)$ as follows:

$$q_i(t_k)=V_i(t_k)s_i(t_k), \quad (20)$$

where $V_i(t_k)$ is the first D^i columns of $B_i^+(t_k)=B_i^H(t_k)(B_i(t_k)B_i^H(t_k))^{-1}$, $s_i(t_k)=[s_{i,1}(t_k) \ldots s_{i,L_i}(t_k)]$ is the data vector to be transmitted to the UEs in the ith cell, and $s_{i,j}(t_k)$ is a vector of size $d_j^i \times 1$ representing a rank-d_j^i signal that should be transmitted to user j.

At each transmitter TX_i, the data to be transmitted to the selected UEj over the subcarriers $w_1, \ldots, w_{n2}$ is split into n**1** rank-d_j^i data $\{s_{i,j}(t_k)\}_{k=1}^{n1}$. After computing $\{q_i(t_k)\}_{k=1}^{n1}$, the transmitted signals over subcarriers $w_1, \ldots, w_{n2}$ $\{x_i(w_n)\}_{n=1}^{n2}$ can be computed from Equation (15). The transmit module **218** shown in FIG. **2** may be used to the transmit signals $q_i(t_k)$.

As a result, the received signal $\tilde{z}_{i,j}^{l}(t_k)$ appears at the UE as:

$$\tilde{z}_{i,j}^{l}(t_k) = \quad (21)$$

$$(v_{ref}^{l})^H F_{i,j}^{-1}(t_k) z_{i,j}(t_k) = k_{i,j}^{l,eq}(t_k) q_i(t_k) + (v_{ref}^{l})^H q_i(t_k) + w_{i,j}^{l,eq}(t_k)$$

$$i = 1,2 \ \ j = 1, \ldots, L_i, k = 1, \ldots, n_1,$$

where

$$k_{i,j}^{l,eq}(t_k) \triangleq (v_{ref}^{l})^H F_{i,j}^{-1}(t_k) K_{i,j}(t_k) \text{ and } w_{i,j}^{l,eq}(t_k) \triangleq (v_{ref}^{l})^H F_{i,j}^{-1}(t_k) w_{i,j}(t_k).$$

At step **414**, the UE decodes the received data signal, such as by using the decode module **120** shown in FIG. **2**. In selected embodiments, each UE(i,j) may know its own precoding vectors for its data streams $\{v_{i,j}^{l}(t_k)\}_{k=1}^{n1}$l=1, . . . , d_j^i, and uses the precoding vectors to decode its l^{th} data stream $\{s_{i,j}^{l}(t_k)\}=_{k=1}^{n1}$ from $(\{\tilde{z}_{i,j}^{l}(t_k)\}_{k=1}^{n1}$ which is obtained from Equation (19). For example, each UE(i,j) converts the received signals in subcarriers $w_1, \ldots, w_{n2}$ to $\{z_{i,j}(t_k)\}_{k=}^{n1}$ from Equation (16), and converts them to $\{\tilde{z}_{i,j}^{l}(t_k)\}_{k=1}^{n1}$ from Equation (21). In this way, the selected UEs can decode their data $\{s_{i,j}^{l}(t_k)\}_{k=1}^{n1}$ from $\{\tilde{z}_{i,j}^{l}(t_k)\}_{k=1}^{n1}$. At step **416**, the process ends.

Using the frequency extension approach, $D^i n_1$ data streams are transmitted in total over n_2 subcarriers and as a result, the normalized number of data streams per subcarrier becomes

$$\frac{D^i n_1}{n_2}.$$

Noting that $D^i \leq M - d_{max}^{3-i}$, the maximum number of data streams per subcarrier for the ith cell becomes

$$\frac{(M - d_{max}^{3-i})n_1}{n_2} = \frac{(M - d_{max}^{3-i})K}{M}.$$

While the description provided with reference to Equations (11)-(21) explains how the direct and interfering channels as well as the corresponding transmit and receive signals of UEs are extended in the frequency domain, it will be appreciated that a similar approach would be used to extend the interfering channels in the time domain. In either case of time or frequency extension, it will be appreciated that there is implied a loss in the spectral efficiency by the ratio of

$$\frac{D^i n_1}{n_2}$$

compared to the M=K case due to the fact that n**1** independent mixed-rank signals are transmitted over n**2** subcarriers. As a consequence, the extension scheme may not be suitable for small values of

$$\frac{D^i n_1}{n_2}.$$

In addition, it will be appreciated that the frequency extension approach has more potential for practical use since the time extension approach implies decoding delay which is not acceptable for many applications.

In selected embodiments, the throughput performance in the case of frequency extension can be improved by selecting a proper set of subcarriers to implement the frequency extension algorithm. For this purpose, it is important to have the matrices $\{K_{i,j}(t_k)\}_{k=1}^{n1}$ as far away as possible from the singularity. One way to satisfy this would be to make the chordal distance between the subspaces spanned by $\{G_{i,j}(w_k)\}_{k=1}^{n2}$ above a certain (configurable) threshold. To this end, all UE devices that are going to be served in the "interference alignment" mode may be configured to select the potential subcarriers and order them based on some pre-configured metrics. In selected embodiments, subcarrier ordering is done in a greedy fashion by first selecting a "best" subcarrier (e.g., the subcarrier having the maximum minimum eigenvalue for the interfering channel), and then selecting the next "best" subcarrier, and so on. After selecting i−1 subcarriers, the ith subcarrier is selected as the one whose minimum eigenvalue of the corresponding interfering channel is greater than a predetermined threshold and its chordal distance to the interfering channel of the previously selected subcarriers is greater than another pre-configured threshold. UEs can feed back some information to the transmitters in the form of RI or CQI to reflect this ordering. With this information provided to the transmitter, the transmitter identifies a set of subcarriers (say $w_1, \ldots w_{n2}$) that the transmitters want to use interference alignment, and then selects L_i (up to M−1 UEs for single rank UEs) that already reported these subcarriers as their potential subcarriers for interference alignment (the ones with high ranks). Then, the transmitter uses the frequency extension approach described hereinabove.

UE Selection and Scheduling

When the transmitter is selecting L_i UEs in cell i that is less than the total number of UEs (N_i), selected embodiments of the present disclosure provide a low-complexity scheduling and pairing scheme for choosing the UEs that achieves good performance and improves the throughput performance of the system. To illustrate an example receiver selection process, reference is now made to FIG. **5** which depicts in flow chart form a receiver selection process **500** that may be performed in cases when the number of receiver antennas equals or exceeds the number of transmitter antennas (e.g. K≥M). Once the procedure starts (step **502**), each $UE_{i,j}$ device estimates the channel from the serving transmitter and the channel from the interfering transmitter (step **504**). The UE also estimates or calculates the rank of the direct channel (d_j^i) at step **504**, such as by using, for example, the same procedure as 3GPP Release 8 LTE or LTE-A. The UE reports back this rank as RI to the serving transmitter and request a signal of rank d_j^i. Based on the computed rank, each $UE_{i,j}$ device computes (step **504**) its effective direct channel vectors for each requested data stream as $h_{i,j}^{l,eq} = (v_{ref}^l)^H G_{i,j}^+ H_{i,j}$ for l=1, . . . , d_j^i and its effective noise power as, $\mathfrak{N}_{i,j}^{l,eff} = E\{|n_{i,j}^{l,eq}|^2\}$.

At step **506**, each $UE_{i,j}$ device computes channel direction information (CDI) and channel quality information (CQI) values for each d_j^i data streams, such as the following examples:

$$CDI_{i,j}^l \triangleq \frac{h_{i,j}^{l,eq}}{\|h_{i,j}^{l,eq}\|}, \quad CQI_{i,j}^l \triangleq \frac{\|h_{i,j}^{l,eq}\|^2 - |h_{i,j}^{l,eq} v_{ref}^l|^2}{\mathfrak{N}_{i,j}^{l,eff}}, \text{ for } l = 1, \ldots, d_j^i. \tag{22}$$

While each $UE_{i,j}$ device may feed back the computed CDI and CQI values for all requested d_j^i date streams to the corresponding transmitter, it will be appreciated that there might be no need for feeding back $CDI_{i,j}^l$ in the TDD mode when the transmitters can acquire it from the UL channel.

At decision block **508**, it is determined if there is a high load that meets or exceeds a threshold level. This decision may be implemented by comparing the total number of UEs (N_i) to a threshold load number (N_{th}).

If there is a high user load ($N_i \geq N_{th}$), a pre-configured threshold γ_{th} is retrieved or computed at step **510** and used by the transmitter TX_i to construct the following set:

$$\mathcal{S}_i \triangleq \{(j, l) \mid \beta_{i,j} CQI_{i,j}^l > \gamma_{th}\}, \tag{23}$$

where $\beta_{i,j}$ denotes the scheduling parameter.

At step **512**, the transmitter TX_i sets a counter value r=1 and selects the first UE (denoted s_r) as follows:

$$(s_r, q_r) = \arg\max_{(j,l)} \beta_{i,j} CQI_{i,j}^l \text{ for } (j,l) \in \mathcal{S}_i. \tag{24}$$

In Equation (24) it is possible that a previously selected UE is selected again for considering another rank. Therefore, the rank of the signal for the UE s_r is increased by one: $d_{s_r} = d_{s_r} + 1$ to keep track of its rank (the initial value for all d_j=0).

At step **514**, the counter value r is incremented, and at step **516**, the transmitter TX_i determines if the counter value exceeds the number of $M - d_{max}^{3-i}$ available ranks.

At step **518**, the remaining UEs are selected with an iterative process for so long as the counter value does not exceed $M - d_{max}^{3-i}$ (e.g., negative outcome to decision block **516**). In

step **518**, the transmitter TX_i defines the set of previously selected UEs as

$$\mathcal{S}_{i,r-1} \triangleq \{(s_1, q_1), \ldots, (s_{r-1}, q_{r-1})\}.$$

In addition, $\boldsymbol{\mathcal{P}}_{r-1}$ is defined as the sub-space spanned by the CDI vectors of the previously selected UEs, i.e.

$$\mathcal{P}_{r-1} \triangleq \text{span}(CDI_{i,s_1}^{q_1}, \ldots, CDI_{i,s_{r-1}}^{q_{r-1}}).$$

Finally, for all $(j,l) \in \mathcal{S}_i - \mathcal{S}_{i,r-1}$, the transmitter TX_i defines $\boldsymbol{\mathcal{P}}_{i,j}^{l,(r-1)}$ as the projection of $CDI_{i,j}^{l}$ over $\boldsymbol{\mathcal{P}}_{r-1}$, and then selects

$$(s_r, q_r) = \arg \min_{(j,l) \in S_i - S_{i,r-1}} \|p_{i,j}^{l,(r-1)}\|^2. \quad (25)$$

For counter values r=2 to $M-d_{max}^{3-i}$, the process is repeated until the counter value exceeds $M-d_{max}^{3-i}$ (e.g., affirmative outcome to decision block **516**). At this point, the UEs selected for the high user load are identified at step **520** as $(s_1, \ldots s_{Li})$, where the number of selected UEs L_i would be defined as the cardinality of the set

$$\{s_1, \ldots, s_{M-d_{max}^{3-i}}\}$$

(which is the number of different users in this set) and the process ends (step **522**).

On the other hand, if it is determined (at decision block **508**) that there is a medium or low user load ($N_i < N_{th}$), the transmitter TX_i sets a counter value r=1 and selects the first UE (denoted s_r) at step **509** as follows:

$$(s_r, q_r) = \arg \max_{(j,l)} \beta_{i,j} CQI_{i,j}^{l}, \text{ for } l=1, \ldots, d_j^i, \quad j=1, \ldots, N_i. \quad (26)$$

In Equation (26) it is possible that a previously selected UE is selected again for considering another rank. Therefore, we increase the rank of the signal for the UE s_r by one: $d_{s_r} = d_{s_r} + 1$ to keep track of its rank (the initial value for all $d_j = 0$).

At step **511**, the counter value r is incremented, and at step **513**, the transmitter TX_i determines if the counter value exceeds the number of $M-d_{max}^{3-i}$ available ranks.

At step **515**, the remaining UEs are selected with an iterative process for so long as the counter value does not exceed $M-d_{max}^{3-i}$ (e.g., negative outcome to decision block **513**). In step **515**, the transmitter TX_i defines the set of previously selected UEs as

$$\mathcal{S}_{i,r-1} \triangleq \{(s_1, q_1), \ldots, (s_{r-1}, q_{r-1})\}.$$

In addition, $\boldsymbol{\mathcal{P}}_{r-1}$ is defined as the sub-space spanned by the CDI vectors of the previously selected UEs, i.e.

$$\mathcal{P}_{r-1} \triangleq \text{span}(CDI_{i,s_1}^{q_1}, \ldots, CDI_{i,s_{r-1}}^{q_{r-1}}).$$

Finally, for all $(j,l) \notin \boldsymbol{\mathcal{P}}_{i,r-1}$, the transmitter TX_i defines $\boldsymbol{\mathcal{P}}_{i,j}^{l,(r-1)}$ as the projection of $CDI_{i,j}^{l}$ over $\boldsymbol{\mathcal{P}}\, P_{r-1}$, and then selects

$$(s_r, q_r) = \arg \max_{(j,l) \notin S_{i,r-1}} \beta_{i,j} CQI_{i,j}^{l} \left(1 - \|p_{i,j}^{l,(r-1)}\|^2\right). \quad (27)$$

For counter values r=2 to $M-d_{max}^{3-i}$, the process is repeated until the counter value exceeds $M-d_{max}^{3-i}$ (e.g., affirmative outcome to decision block **513**). At this point, the UEs selected for the medium or low user load are identified at step **520** as $(s_1, \ldots s_{Li})$, where the number of selected UEs L_i would be defined as the cardinality of the set

$$\{s_1, \ldots, s_{M-d_{max}^{3-i}}\}$$

(which is the number of different users in this set) and the process ends (step **522**).

As described herein, the threshold values N_{th} and γ_{th} may be configurable and can be optimized based on the system parameters. By tuning the threshold values, the disclosed selection process chooses UEs having an effective SNR values (approximated by CQI values) that are high enough while maximizing the orthogonality of their equivalent direct channels. The SNR values are calculated for all requested data stream (the requested RI) and all data streams having high enough SNR values will be selected in scheduling procedure. While the selection process for a medium or low user load can be used in the high user load case, it will be appreciated that the selection process for a high user load reduces algorithm complexity and the feedback load (in the FDD mode), since only a portion of the users are considered in the scheduling. This helps reducing the feedback load of CQI to just one bit since the UEs just need to send an acknowledgement bit to their affiliated transmitter indicating that whether or not their effective SNR is above the threshold or not and the actual value of CQI is not important.

In order to select L_i UEs, the transmitter i needs to know the maximum rank d_{max}^{3-i} that the other transmitter is sending. However, at the beginning of the scheduling procedure it is not known. In one embodiment, both transmitters can set d_{max}^{3-i} to its minimum value 1, i.e. $d_{max}^{3-i}=1$. Transmitters can support L_i UEs such that $D^i + d_{max}^{3-i}$ is less than M. After the procedure **500** ends at step **513** or step **516**. The transmitters can negotiate on the values of d_{max}^{3-i}. If the transmitter (3−i) asks for a $d_{max}^{3-i} > 1$, the current transmitter i should remove the last $d_{max}^{3-i} - 1$ selected users in

$$\mathcal{S}_{i,M-d_{max}^{3-i}-1}$$

and adjust the number of its affiliated UEs L_i.

In another embodiment, transmitters can fix the value of d_{max}^{i} and rejects any request by any UE which is requesting a rank more than d_{max}^{3-i}. In other words, if UEs reporting d_j^i CDIs and CQIs for d_j^i data streams in (22), transmitters consider only the first d_{max}^{i} values for CDI and CQI that maximizes $\beta_{i,j} CQI_{i,j}^{l}$ in (24) or (26). Note that the accepted rank of each UE is saved in d_{s_r}.

Additional receiver scheduling algorithms are disclosed for selecting L_i from N_i total number of UEs when the UE antenna count is less than the transmitter antenna count. To illustrate an example receiver selection process for these embodiments, reference is now made to FIG. **6** which depicts in flow chart form a receiver selection process **600** that may be performed to extend the interfering channels in frequency or time in cases when the number of transmitter antennas exceeds the number of receiver antennas (e.g. K<M). Once the procedure starts (step **601**), each transmitter device TX_i, effectively extends the interfering channels by finding or deriving **n1** and **n2** (at step **602**) that are the smallest integer numbers such that: **n1**M=**n2**K(**n2**>**n1**). After computing **n1** and **n2**, each transmitter TX_i selects the subcarriers $w_1, \ldots, w_{n2}$ for implementing the proposed scheme and considers the set of N_i UEs that can potentially be considered for the scheduling.

At step **604**, each $UE_{i,j}$ device estimates the channel from the serving transmitter and the channel from the interfering transmitter. The UE estimates the rank of the channel (d_j^i) for example using the same procedure as 3GPP Release 8 LTE or LTE-A. The UE reports back this rank as RI to the serving transmitter and request a signal of rank d_j^i. Then, each $UE_{i,j}$ device estimates their direct and cross channels, and following Equations (11)-(17), each $UE_{i,j}$ device computes its effective direct channel for each t_k as $k_{i,j}^{l,eq}(t_k)=(v_{ref}^l)^H F_{i,j}^{-1}(t_k)K_{i,j}(t_k)$ and their effective noise power as $\Re_{i,j}^{l,eff}(t_k)=E\{|w_{i,j}^{l,eq}(t_k)|^2\}$ for $l=1,\ldots,d_j^i$. In addition, each $UE_{i,j}$ device computes channel direction information (CDI) and channel quality information (CQI) values for each d_j^i data streams and each t_k as follows:

$$CDI_{i,j}^l(t_k) \triangleq \frac{k_{i,j}^{l,eq}(t_k)}{\left\|k_{i,j}^{l,eq}(t_k)\right\|}, \tag{28}$$

$$CQI_{i,j}^l(t_k) \triangleq \frac{\left\|k_{i,j}^{l,eq}(t_k)\right\|^2 - \left|k_{i,j}^{l,eq}(t_k)v_{ref}\right|^2}{\Re_{i,j}^{l,eff}(t_k)}, \text{ for } l = 1, \ldots, d_j^i.$$

While each $UE_{i,j}$ device may feed back the computed CDI and CQI values for all requested d_j^i date streams to the corresponding transmitter for each t_k, it will be appreciated that there might be no need for feeding back $CDI_{i,j}^l(t_k)$ in the TDD mode when the transmitters can acquire it from the UL channel.

At decision block **606**, it is determined if there is a high load that meets or exceeds a threshold level. This decision may be implemented by comparing the total number of UEs (N_i) to a threshold load number (N_{th}).

If there is a high user load ($N_i \geq N_{th}$), a pre-configured threshold γ_{th} is retrieved or computed at step **608** and used by the transmitter TX_i to compute following metric for UE (i,j):

$$q_{i,j}^l \triangleq \sum_{k=1}^{n1} \beta_{i,j}\log(1 + CQI_{i,j}^l(t_k)), \tag{29}$$

in which $\beta_{i,j}$ denotes the scheduling parameter. At step **608**, the transmitter TX_i also constructs the following set:

$$\mathcal{S}_i \triangleq \{(j,l) \mid q_{i,j}^l > \gamma_{th}\}. \tag{30}$$

At step **610**, the transmitter TX_i sets a counter value r=1 and selects the first UE (denoted s_r) as follows:

$$(s_1,q_r)=\arg\max_{(i,j)} q_{i,j}{}^l \text{ for } (j,l)\in \mathcal{S}_i. \tag{31}$$

In Equation (31) it is possible that a previously selected UE is selected again for considering another rank. Therefore, we increase the rank of the signal for the UE s_r by one: $d_{s_r}=d_{s_r}+1$ to keep track of its rank (the initial value for all $d_j=0$).

At step **612**, the counter value r is incremented, and at step **614**, the transmitter TX_i determines if the counter value exceeds the number of $M-d_{max}^{3-i}$ available ranks.

At step **616**, the remaining UEs are selected with an iterative process for so long as the counter value does not exceed $M-d_{max}^{3-i}$ (e.g., negative outcome to decision block **614**). In step **616**, the transmitter TX_i the set of previously selected UEs as

$$\mathcal{S}_{i,r-1} \triangleq \{(s_1, q_1), \ldots, (s_{r-1}, q_{r-1})\}.$$

In addition, the transmitter TX_i defines

$$\mathcal{P}_{r-1}(t_k) \triangleq \text{span}(CDI_{i,s_1}^{q_1}(t_k), \ldots, CDI_{i,s_{r-1}}^{q_{r-1}}(t_k)).$$

Finally, for all $(j,l)\in \mathcal{S}_i - \mathcal{S}_{i,r-1}$, the transmitter TX_i defines $\mathcal{P}_{i,j}^{l,(r-1)}(t_k)$ as the projection of $CDI_{i,j}^l(t_k)$ over $\mathcal{P}_{r-1}(t_k)$, and then selects the next UE by computing:

$$s_l = \arg\min_{(j,l)\in \mathcal{S}_i - \mathcal{S}_{i,r-1}} \sum_{k=1}^{n1} \left\|p_{i,j}^{l(r-1)}(t_k)\right\|^2. \tag{32}$$

For counter values r=2 to $M-d_{max}^{3-i}$, the process is repeated until the counter value exceeds $M-d_{max}^{3-i}$ (e.g., affirmative outcome to decision block **614**). At this point, the UEs selected for the high user load are identified at step **618** as $(s_1,\ldots s_{Li})$, where the number of selected UEs L_i would be defined as the cardinality of the set

$$\{s_1, \ldots, s_{M-d_{max}^{3-i}}\}$$

(which is the number of different users in this set) and the process ends (step **620**).

If it is determined (at decision block **606**) that there is a medium or low user load ($N_i<N_{th}$), the transmitter TX_i sets a counter value r=1 and selects the first UE (denoted s_r) at step **607** as follows:

$$(s_r,q_r)=\arg\max_{(j,l)} q_{i,j}{}^l, \text{ for } l=1,\ldots,d_j^i, j=1,\ldots,N_i. \tag{33}$$

In Equation (33) it is possible that a previously selected UE is selected again for considering another rank. Therefore, we increase the rank of the signal for the UE s_r by one: $d_{s_r}=d_{s_r}+1$ to keep track of its rank (the initial value for all $d_j=0$).

At step **609**, the counter value r is incremented, and at step **611**, the transmitter TX_i determines if the counter value exceeds the number of $M-d_{max}^{3-i}$ available ranks.

At step **613**, the remaining UEs are selected with an iterative process for so long as the counter value does not exceed $M-d_{max}^{3-i}$ (e.g., negative outcome to decision block **611**). In step **615**, the transmitter TX_i defines the set of previously selected UEs as

$$\mathcal{S}_{i,r-1} \triangleq \{(s_1, q_1), \ldots, (s_{r-1}, q_{r-1})\}.$$

The transmitter also defines

$$\mathcal{P}_{r-1}(t_k) \triangleq \text{span}(CDI_{i,s_1}^{q_1}(t_k), \ldots, CDI_{i,s_{r-1}}^{q_{r-1}}(t_k)).$$

Finally, for all $(j,l)\notin \mathcal{S}_{i,r-1}$, the transmitter TX_i defines $\mathcal{P}_{i,j}^{l(r-1)}(t_k)$ as the projection of $CDI_{i,j}^l(t_k)$ over $\mathcal{P}_{r-1}(t_k)$, and then selects the next UE by computing:

$$(s_r, q_r) = \arg\max_{(j,l)\notin \mathcal{S}_{i,r-1}} \sum_{k=1}^{n1} \beta_{i,j}\log\left(1 + CQI_{i,j}^l(t_k)\left(1 - \left\|\varphi_{i,j}^{l(r-1)}\right\|^2\right)\right). \tag{34}$$

For counter values r=2 to $M-d_{max}^{3-i}$, the process is repeated until the counter value exceeds L_i (e.g., affirmative outcome to decision block **611**). At this point, the UEs selected for the medium or low user load are identified at step

618 as $(s_1, \ldots s_{L_i})$, where the number of selected UEs L_i would be defined as the cardinality of the set

$$\{s_1, \ldots, s_{M-d_{max}^{3-i}}\}$$

(which is the number of different users in this set) and the process ends (step 620).

Again, it will be appreciated that threshold parameters N_{th} and γ_{th} can be optimized based on the system parameters. The UE selection algorithm proposed for the case of K<M is very similar to the one proposed for the case of K≥M, with the difference that the same set of UEs must be scheduled for all subcarriers $w_1, \ldots, w_{n2}$. As a result, it is possible to select UEs with fairly good channels in all subcarriers for the case of K<M.

In the case where Euclidean Distance Minimization techniques are used to find a combining vector for cases where the UE antenna count K is less than the transmitter antenna count M, the scheduling algorithm can be the same as in the case of K≥M except for the calculation of the CQI values. In particular, since in this case the inter-cell interference cannot be eliminated, CQI may reflect the inter-cell interference for better scheduling performance. For this purpose, CQIs for UE (i,j) may be defined as follows:

$$CQI_{i,j}^{l} \triangleq \frac{\frac{P_i}{D^i}\left(\left\|h_{i,j}^{l,eff}\right\|^2 - \left|h_{i,j}^{l,eff} v_{ref}^{l}\right|^2\right)}{\left(1 - \frac{\left|(v_{ref}^{l})^H G_{i,j}^{+} G_{i,j} v_{ref}^{l}\right|^2}{\left\|(v_{ref}^{l})^H G_{i,j}^{+} G_{i,j}\right\|^2}\right)\frac{P_{3-i}}{M-1} + E\left\{\left|h_{i,j}^{l,eq}\right|^2\right\}}, \quad (35)$$

where $h_{i,j}^{l,eff} = (v_{ref}^{l})^H G_{i,j}^{+} H_{i,j}$. Having CQI defined as above, one may follow the same scheduling algorithm as in the case of K≥M (shown in FIG. 5).

In the interference alignment schemes disclosed herein which use a fixed, globally-known predetermined and "indexed" list of linearly independent vectors $V_{ref} = \{v_{ref}^{1}, \ldots, v_{ref}^{M}\}$, multiple codebook-based V_{ref}s (or downloadable) scheme may be used to improve system performance in a way similar to the use of multiple codebooks for precoding matrix information (PMI) in LTE or LTE-A. In selected embodiments, a rotational codebook-based V_{ref} scheme is employed wherein each transmitter TX_i and its associated UEs switch to one of different possible sets based on a pre-determined order or sequence. The order can be cell-specific or the same for all cells, but in either case, no additional signaling is required to tell the UEs which set V_{ref} is being used at a certain time since the order is known to all UEs.

As seen from the foregoing, the disclosed interference alignment techniques provide significant multiplexing gains with good performance and reduced complexity to address interference between two transmitters, each serving the maximum possible number of UEs simultaneously, while only requiring local CSI knowledge at nodes. For example, the disclosed IA schemes provide acceptable performance with local-only or partial CSI assumptions at the transmitters, thereby avoiding the requirement of large feedback overhead that the current LTE cellular networks and even LTE-A cannot handle. In addition, the disclosed IA schemes do not require a large amount of coordination between the nodes that increases dramatically when the number of coordinating nodes increases. And by eliminating the requirement of large global channel feedback, the feedback challenges associated with high mobility scenarios and feedback delay are avoided.

Referring now to FIG. 7, there is shown a schematic block diagram illustrating exemplary components of a mobile wireless communications or user equipment device 700 which may be used with selected embodiments of the present disclosure. The wireless device 700 is shown with specific components for implementing features described above. It is to be understood that the wireless device 700 is shown with very specific details for exemplary purposes only. As depicted, user equipment 700 includes a number of components such as a main processor 702 that controls the overall operation of user equipment 700. Communication functions, including data and voice communications, are performed through a communication subsystem 704. The communication subsystem 104 receives messages from and sends messages to a wireless network 701. In this illustrative embodiment of user equipment 700, communication subsystem 704 is configured in accordance with the Global System for Mobile Communication (GSM) and General Packet Radio Services (GPRS) standards. The GSM/GPRS wireless network is used worldwide and these standards may be superseded eventually by Enhanced Data GSM Environment (EDGE) and Universal Mobile Telecommunications Service (UMTS). New standards are still being defined, but it is believed that they will have similarities to the network behavior described herein, and it will also be understood by persons skilled in the art that the embodiments described herein are intended to use any other suitable standards that are developed in the future. The wireless link connecting the communication subsystem 704 with the wireless network 701 represents one or more different Radio Frequency (RF) channels, operating according to defined protocols specified for GSM/GPRS communications. With newer network protocols, these channels are capable of supporting both circuit switched voice communications and packet switched data communications.

Although the wireless network 701 associated with user equipment 700 is a GSM/GPRS wireless network in one implementation, other wireless networks may also be associated with user equipment 700 in variant implementations. The different types of wireless networks that may be employed include, for example, data-centric wireless networks, voice-centric wireless networks, and dual-mode networks that can support both voice and data communications over the same physical base stations. Combined dual-mode networks include, but are not limited to, Code Division Multiple Access (CDMA) or CDMA2000 networks, GSM/GPRS networks (as mentioned above), and future generation networks like EDGE, UMTS, WiMAX, LTE and LTE-A. Some other examples of data-centric networks include WiFi 802.11, Mobitex™ and DataTAC™ network communication systems. Examples of other voice-centric data networks include Personal Communication Systems (PCS) networks like GSM and Time Division Multiple Access (TDMA) systems.

The main processor 702 also interacts with additional subsystems such as a Random Access Memory (RAM) 706, a flash memory 708, a display 710, an auxiliary input/output (I/O) subsystem 712, a data port 714, a keyboard 716, a speaker 718, a microphone 720, short-range communications 722, and other device subsystems 724.

Some of the subsystems of the user equipment 700 perform communication-related functions, whereas other subsystems may provide "resident" or on-device functions. By way of example, the display 710 and the keyboard 716 may be used for both communication-related functions, such as entering a text message for transmission over the network 701, and device-resident functions such as a calculator or task list.

The user equipment 700 can send and receive communication signals over the wireless network 701 after required

network registration or activation procedures have been completed. Network access is associated with a subscriber or user of the user equipment **700**. To identify a subscriber, the user equipment **700** requires a SIM/RUIM card **726** (i.e. Subscriber Identity Module or a Removable User Identity Module) to be inserted into a SIM/RUIM interface **728** in order to communicate with a network. The SIM card or RUIM **726** is one type of a conventional "smart card" that can be used to identify a subscriber of the user equipment **700** and to personalize the user equipment **700**, among other things. Without the SIM card **726**, the user equipment **700** is not fully operational for communication with the wireless network **701**. By inserting the SIM card/RUIM **726** into the SIM/RUIM interface **728**, a subscriber can access all subscribed services. Services may include: web browsing and messaging such as e-mail, voice mail, Short Message Service (SMS), and Multimedia Messaging Services (MMS). More advanced services may include: point of sale, field service and sales force automation. The SIM card/RUIM **726** includes a processor and memory for storing information. Once the SIM card/RUIM **726** is inserted into the SIM/RUIM interface **728**, it is coupled to the main processor **702**. In order to identify the subscriber, the SIM card/RUIM **726** can include some user parameters such as an International Mobile Subscriber Identity (IMSI). An advantage of using the SIM card/RUIM **726** is that a subscriber is not necessarily bound by any single physical user equipment. The SIM card/RUIM **726** may store additional subscriber information for user equipment as well, including datebook (or calendar) information and recent call information. Alternatively, user identification information can also be programmed into the flash memory **708**.

The user equipment **700** is a battery-powered device and includes a battery interface **732** for receiving one or more rechargeable batteries **730**. In at least some embodiments, the battery **730** can be a smart battery with an embedded microprocessor. The battery interface **732** is coupled to a regulator (not shown), which assists the battery **730** in providing power V+ to the user equipment **700**. Although current technology makes use of a battery, future technologies such as micro fuel cells may provide the power to the user equipment **700**.

The user equipment **700** also includes an operating system **734** and software components **736** which are described in more detail below. The operating system **734** and the software components **736** that are executed by the main processor **702** are typically stored in a persistent store such as the flash memory **708**, which may alternatively be a read-only memory (ROM) or similar storage element (not shown). Those skilled in the art will appreciate that portions of the operating system **734** and the software components **736** such as specific device applications, or parts thereof, may be temporarily loaded into a volatile store such as the RAM **706**. Other software components can also be included, as is well known to those skilled in the art.

The subset of software components **736** that control basic device operations, including data and voice communication applications, will normally be installed on the user equipment **700** during its manufacture. Other software applications include a message application **738** that can be any suitable software program that allows a user of the user equipment **700** to send and receive electronic messages. Various alternatives exist for the message application **738** as is well known to those skilled in the art. Messages that have been sent or received by the user are typically stored in the random access or flash memory **708** of the user equipment **700** or some other suitable storage element in the user equipment **700**. In at least some embodiments, some of the sent and received messages may be stored remotely from the device **700** such as in a data store of an associated host system that the user equipment **700** communicates with.

The software applications can further include a device state module **740**, a Personal Information Manager (PIM) **742**, and other suitable modules (not shown). The device state module **740** provides persistence, i.e. the device state module **740** ensures that important device data is stored in persistent memory, such as the flash memory **708**, so that the data is not lost when the user equipment **700** is turned off or loses power.

The PIM **742** includes functionality for organizing and managing data items of interest to the user, such as, but not limited to, e-mail, contacts, calendar events, voice mails, appointments, and task items. A PIM application has the ability to send and receive data items via the wireless network **701**. PIM data items may be seamlessly integrated, synchronized, and updated via the wireless network **701** with the user equipment subscriber's corresponding data items stored or associated with a host computer system. This functionality creates a mirrored host computer on the user equipment **700** with respect to such items. This can be particularly advantageous when the host computer system is the user equipment subscriber's office computer system.

The user equipment **700** also includes a connect module **744**, and an IT policy module **746**. The connect module **744** implements the communication protocols that are required for the user equipment **700** to communicate with the wireless infrastructure and any host system, such as an enterprise system, that the user equipment **700** is authorized to interface with. Examples of a wireless infrastructure and an enterprise system are given in FIG. **8** described in more detail below.

The connect module **744** includes a set of APIs that can be integrated with the user equipment **700** to allow the user equipment **700** to use any number of services associated with the enterprise system. The connect module **744** allows the user equipment **700** to establish an end-to-end secure, authenticated communication pipe with the host system. A subset of applications for which access is provided by the connect module **744** can be used to pass IT policy commands from the host system to the user equipment **700**. This can be done in a wireless or wired manner. These instructions can then be passed to the IT policy module **746** to modify the configuration of the device **700**. Alternatively, in some cases, the IT policy update can also be done over a wired connection.

The IT policy module **746** receives IT policy data that encodes the IT policy. The IT policy module **746** then ensures that the IT policy data is authenticated by the user equipment **700**. The IT policy data can then be stored in the flash memory **708** in its native form. After the IT policy data is stored, a global notification can be sent by the IT policy module **746** to all of the applications residing on the user equipment **700**. Applications for which the IT policy may be applicable then respond by reading the IT policy data to look for IT policy rules that are applicable.

The IT policy module **746** can include a parser (not shown), which can be used by the applications to read the IT policy rules. In some cases, another module or application can provide the parser. Grouped IT policy rules, described in more detail below, are retrieved as byte streams, which are then sent (recursively, in a sense) into the parser to determine the values of each IT policy rule defined within the grouped IT policy rule. In at least some embodiments, the IT policy module **746** can determine which applications are affected by the IT policy data and send a notification to only those applications. In either of these cases, for applications that aren't running at the time of the notification, the applications can call the parser

or the IT policy module **746** when they are executed to determine if there are any relevant IT policy rules in the newly received IT policy data.

All applications that support rules in the IT Policy are coded to know the type of data to expect. For example, the value that is set for the "WEP User Name" IT policy rule is known to be a string; therefore, the value in the IT policy data that corresponds to this rule is interpreted as a string. As another example, the setting for the "Set Maximum Password Attempts" IT policy rule is known to be an integer, and therefore the value in the IT policy data that corresponds to this rule is interpreted as such.

After the IT policy rules have been applied to the applicable applications or configuration files, the IT policy module **746** sends an acknowledgement back to the host system to indicate that the IT policy data was received and successfully applied.

Other types of software applications can also be installed on the user equipment **700**. These software applications can be third party applications, which are added after the manufacture of the user equipment **700**. Examples of third party applications include games, calculators, utilities, etc.

The additional applications can be loaded onto the user equipment **700** through at least one of the wireless network **701**, the auxiliary I/O subsystem **712**, the data port **714**, the short-range communications subsystem **722**, or any other suitable device subsystem **724**. This flexibility in application installation increases the functionality of the user equipment **700** and may provide enhanced on-device functions, communication-related functions, or both. For example, secure communication applications may enable electronic commerce functions and other such financial transactions to be performed using the user equipment **700**.

The data port **714** enables a subscriber to set preferences through an external device or software application and extends the capabilities of the user equipment **700** by providing for information or software downloads to the user equipment **700** other than through a wireless communication network. The alternate download path may, for example, be used to load an encryption key onto the user equipment **700** through a direct, and thus reliable and trusted connection, to provide secure device communication.

The data port **714** can be any suitable port that enables data communication between the user equipment **700** and another computing device. The data port **714** can be a serial or a parallel port. In some instances, the data port **714** can be a USB port that includes data lines for data transfer and a supply line that can provide a charging current to charge the battery **730** of the user equipment **700**.

The short-range communications subsystem **722** provides for communication between the user equipment **700** and different systems or devices, without the use of the wireless network **701**. For example, the subsystem **722** may include an infrared device and associated circuits and components for short-range communication. Examples of short-range communication standards include standards developed by the Infrared Data Association (IrDA), Bluetooth, and the 802.11 family of standards developed by IEEE.

In use, a received signal such as a text message, an e-mail message, or web page download will be processed by the communication subsystem **704** and input to the main processor **702**. The main processor **702** will then process the received signal for output to the display **710** or alternatively to the auxiliary I/O subsystem **712**. A subscriber may also compose data items, such as e-mail messages, for example, using the keyboard **716** in conjunction with the display **710** and possibly the auxiliary I/O subsystem **712**. The auxiliary subsystem **712** may include devices such as: a touch screen, mouse, track ball, infrared fingerprint detector, or a roller wheel with dynamic button pressing capability. The keyboard **716** is preferably an alphanumeric keyboard or telephone-type keypad. However, other types of keyboards may also be used. A composed item may be transmitted over the wireless network **200** through the communication subsystem **704**.

For voice communications, the overall operation of the user equipment **700** is substantially similar, except that the received signals are output to the speaker **718**, and signals for transmission are generated by the microphone **720**. Alternative voice or audio I/O subsystems, such as a voice message recording subsystem, can also be implemented on the user equipment **700**. Although voice or audio signal output is accomplished primarily through the speaker **718**, the display **710** can also be used to provide additional information such as the identity of a calling party, duration of a voice call, or other voice call related information.

Referring now to FIG. **8**, there is depicted a block diagram of an illustrative implementation of a node **802** of the wireless network **701**. In practice, the wireless network **701** comprises one or more nodes **802**. In conjunction with the connect module **744**, the user equipment **700** can communicate with the node **802** within the wireless network **701**. In the illustrative implementation **800**, the node **802** is configured in accordance with General Packet Radio Service (GPRS) and Global Systems for Mobile (GSM) technologies. However, in other embodiments, node **802** may be configured in accordance with Long Term Evolution (LTE) technology, LTE-Advanced, or IEEE WiMAX. The node **802** includes a base station controller (BSC) **804** with an associated tower station **806**, a Packet Control Unit (PCU) **808** added for GPRS support in GSM, a Mobile Switching Center (MSC) **810**, a Home Location Register (HLR) **812**, a Visitor Location Registry (VLR) **814**, a Serving GPRS Support Node (SGSN) **816**, a Gateway GPRS Support Node (GGSN) **818**, and a Dynamic Host Configuration Protocol (DHCP) **820**. This list of components is not meant to be an exhaustive list of the components of every node **802** within a GSM/GPRS network, but rather a list of components that are commonly used in communications through the network **701**.

In a GSM network, the MSC **810** is coupled to the BSC **804** and to a landline network, such as a Public Switched Telephone Network (PSTN) **822** to satisfy circuit switched requirements. The connection through the PCU **808**, the SGSN **816** and the GGSN **818** to a public or private network (Internet) **824** (also referred to herein generally as a shared network infrastructure) represents the data path for GPRS capable user epuipment. In a GSM network extended with GPRS capabilities, the BSC **804** also contains the Packet Control Unit (PCU) **808** that connects to the SGSN **816** to control segmentation, radio channel allocation and to satisfy packet switched requirements. To track the location of the user equipment **700** and availability for both circuit switched and packet switched management, the HLR **812** is shared between the MSC **810** and the SGSN **816**. Access to the VLR **814** is controlled by the MSC **810**.

The station **806** is a fixed transceiver station and together with the BSC **804** form fixed transceiver equipment. The fixed transceiver equipment provides wireless network coverage for a particular coverage area commonly referred to as a "cell". The fixed transceiver equipment transmits communication signals to, and receives communication signals from, user equipments within its cell via the station **806**. The fixed transceiver equipment normally performs such functions as modulation and possibly encoding or encryption of signals to be transmitted to the user equipment **700** in accordance with

particular, usually predetermined, communication protocols and parameters, under control of its controller. The fixed transceiver equipment similarly demodulates and possibly decodes and decrypts, if necessary, any communication signals received from the user equipment **700** within its cell. Communication protocols and parameters may vary between different nodes. For example, one node may employ a different modulation scheme and operate at different frequencies than other nodes.

For all user equipment **700** registered with a specific network, permanent configuration data such as a user profile is stored in the HLR **812**. The HLR **812** also contains location information for each registered user equipment and can be queried to determine the current location of a user equipment device. The MSC **810** is responsible for a group of location areas and stores the data of the user equipment devices currently in its area of responsibility in the VLR **814**. Further, the VLR **814** also contains information on user equipment devices that are visiting other networks. The information in the VLR **814** includes part of the permanent user equipment data transmitted from the HLR **812** to the VLR **814** for faster access. By moving additional information from a remote HLR **812** node to the VLR **814**, the amount of traffic between these nodes can be reduced so that voice and data services can be provided with faster response times and at the same time requiring less use of computing resources.

The SGSN **816** and the GGSN **818** are elements added for GPRS support; namely, packet switched data support, within GSM. The SGSN **816** and the MSC **810** have similar responsibilities within the wireless network **701** by keeping track of the location of each user equipment **700**. The SGSN **816** also performs security functions and access control for data traffic on the wireless network **701**. The GGSN **818** provides internetworking connections with external packet switched networks and connects to one or more SGSN's **816** via an Internet Protocol (IP) backbone network operated within the network **701**. During normal operations, a given user equipment **700** must perform a "GPRS Attach" to acquire an IP address and to access data services. This requirement is not present in circuit switched voice channels as Integrated Services Digital Network (ISDN) addresses are used for routing incoming and outgoing calls. Currently, all GPRS capable networks use private, dynamically assigned IP addresses, thus requiring the DHCP server **820** connected to the GGSN **818**. There are many mechanisms for dynamic IP assignment, including using a combination of a Remote Authentication Dial-In User Service (RADIUS) server and a DHCP server. Once the GPRS Attach is complete, a logical connection is established from a user equipment **700**, through the PCU **808**, and the SGSN **816** to an Access Point Node (APN) within the GGSN **818**. The APN represents a logical end of an IP tunnel that can either access direct Internet compatible services or private network connections. The APN also represents a security mechanism for the network **701**, insofar as each user equipment **700** must be assigned to one or more APNs and user equipments **700** cannot exchange data without first performing a GPRS Attach to an APN that it has been authorized to use. The APN may be considered to be similar to an Internet domain name such as "myconnection.wireless.com".

Once the GPRS Attach operation is complete, a tunnel is created and all traffic is exchanged within standard IP packets using any protocol that can be supported in IP packets. This includes tunneling methods such as IP over IP as in the case with some IPSecurity (IPsec) connections used with Virtual Private Networks (VPN). These tunnels are also referred to as Packet Data Protocol (PDP) Contexts and there are a limited number of these available in the network **701**. To maximize use of the PDP Contexts, the network **701** will run an idle timer for each PDP Context to determine if there is a lack of activity. When a user equipment **700** is not using its PDP Context, the PDP Context can be de-allocated and the IP address returned to the IP address pool managed by the DHCP server **820**.

By now it should be appreciated that there is disclosed herein a method, apparatus, computer program product, and system for aligning interference at a rank d receiver having K receive antennas caused by first and second transmitters each having M transmit antennas, where the rank is not necessarily fixed over time. As disclosed, a receiver assembles a first channel matrix and a second channel matrix for a first affiliated transmitter and a second interfering transmitter, respectively. This information may be assembled by receiving pilot signals from the first affiliated transmitter and the second interfering transmitter, and then determining a direct channel matrix H for the first affiliated transmitter and a cross channel matrix G for the second interfering transmitter based on the pilot signals. The receiver also computes an equivalent direct channel matrix from the first and second channel matrices and d predetermined vectors selected from a plurality of predetermined vectors having size M, where the plurality of predetermined vectors is known to the first and second transmitters and to each receiver affiliated with the first and second transmitters, and may be constructed as a set of orthogonal basis vectors for an M-dimensional transmission space. In selected embodiments, the equivalent direct channel matrix is determined by computing one or more equivalent direct channel vectors by computing for each of the d predetermined vectors a product of a complex transpose of each predetermined vector and an inverse of the second channel matrix G^+ and the first channel matrix H. In selected embodiments where the number of receiver antennas is less than the number of transmit antennas (K is less than M), the equivalent direct channel matrix may be computed from the first channel matrix H and second channel matrix G by finding a combining vector r for each of d data streams which minimizes an Euclidean distance of an equivalent cross channel (rG) to a Hermitian transpose of the predetermined vector if K is less than M; and then computing the equivalent direct channel matrix for each of d data streams from the product of the combining vector r and the first channel matrix H. In other embodiments where K is less than M, the equivalent direct channel matrix may be computed from the first channel matrix H and second channel matrix G by extending the first channel matrix H and second channel matrix G in a time or frequency domain to compute an aggregate direct channel matrix and an aggregate cross channel matrix which are invertible with a probability of almost one in a multipath rich propagation environment if K is less than M; and then computing the equivalent direct channel matrix from the aggregate direct channel matrix and the aggregate cross channel matrix and the d predetermined vectors. Once determined, the equivalent direct channel matrix may be fed back to the first affiliated transmitter by the receiver. In addition, CQI, RI and/or PMI information may be fed back from the receiver to the first affiliated transmitter, such as by computing an equivalent noise power at the receiver by computing for each of the d predetermined vectors a product of a Hermitian of that predetermined vector and an inverse of the second channel matrix, and then feeding back to the first affiliated transmitter the effective noise power indicator corresponding to that predetermined vector. At the transmitter, each of the rank d data signals is precoded with a precoding matrix for each receiver that is computed as a null space of the d predetermined vectors and a Hermitian of the equivalent direct chan-

nel matrices of the any other receivers affiliated with the same transmitter. Upon receiving rank d data signals from the first transmitter, the receiver applies a combining matrix to decode rank d data signals received at the receiver, where the combining matrix is derived from the d predetermined vectors and an inverse of the cross channel matrix G to project all cross channels from the second transmitter to the d predetermined vectors to reduce or eliminate interference from the second transmitter.

There is also disclosed herein a transmitter device and method of operation for transmitting one or more signals from a first transmitter having M transmit antennas to one or more mixed rank receivers affiliated with the first transmitter, where each of the receivers has K receive antennas and receives interference from a second transmitter having M transmit antennas. As disclosed, the transmitter acquires an equivalent direct channel matrix from each of the one or more receivers affiliated with the transmitter, such as by receiving the equivalent direct channel matrix from each of the one or more mixed rank receivers in a feedback uplink signal. In selected embodiments, the equivalent direct channel matrices are acquired from each of the one or more mixed rank receivers by receiving an equivalent direct channel matrix that is computed at an affiliated receiver from d predetermined vectors selected from a plurality of predetermined vectors having size M, where d may be different for each receiver. In other embodiments, the transmitter acquires the equivalent direct channel matrix by receiving an equivalent direct channel matrix that is computed at an affiliated rank d receiver from d predetermined vectors selected from a plurality of predetermined vectors having size M, a first channel matrix representing a direct channel to the affiliated receiver from the first transmitter, and a second channel matrix representing a cross channel to the affiliated receiver from the second transmitter. In yet other embodiments, the transmitter acquires the equivalent direct channel matrix by (1) receiving from each affiliated receiver d pilot signals in the direction of a transpose of d combining vectors computed at each receiver as a product of d predetermined vectors selected from a plurality of predetermined vectors having size M and an inverse of a cross channel matrix to said receiver from the second transmitter, and then (2) estimating an equivalent direct channel matrix for each of the one or more receivers from the received pilot signals. Thus, the transmitter acquires a first channel matrix representing a direct channel to the affiliated receiver from the first transmitter, and a second channel matrix representing a cross channel to the affiliated receiver from the second transmitter. The plurality of predetermined vectors may be implemented as a set of orthogonal basis vectors for an M-dimensional transmission space that are known to each receiver affiliated with the first and second transmitters. In other embodiments, the equivalent direct channel matrices are acquired by receiving, from each of the one or more receivers affiliated with the first transmitter, multiple pilot signals in the direction of a transpose of combining vectors which are computed at said receiver as a product of d predetermined vectors selected from a plurality of predetermined vectors having size M and an inverse of a cross channel matrix to said receiver from the second transmitter, and then estimating an equivalent direct channel matrix for each of the one or more d rank receivers from the received pilot signal. Using the acquired equivalent direct channel matrices, the transmitter selects a subset of the one or more mixed rank receivers to receive one or more signals from the first transmitter, and selects a rank of the signal for each receiver in the selected subset. For selected receivers, the transmitter applies a precoding matrix to each signal to be transmitted, where the precoding matrix is derived from the d^{max} predetermined vectors, where d^{max} denotes the maximum rank in the other cell, and any equivalent direct channel matrix selected receivers affiliated with the first transmitter to reduce or eliminate interference to any receivers receiving signals from the first transmitter or from the second transmitter. In addition, the transmitter transmits a signal x=Vs to selected receivers, where V denotes the precoding matrix and where s represents signals of determined ranks specific for each selected receiver. To this end, the transmitter may compute the precoding matrix for the signal to be transmitted to the selected receivers by computing a null space of the d^{max} predetermined vectors and a Hermitian of the equivalent direct channel matrices of the any other receivers affiliated with the same transmitter to effectively eliminate interference to any receiver receiving a signal from the first transmitter or from the second transmitter.

In still further embodiments, there is disclosed a user equipment device that is configured to receive rank d signaling over a direct channel and align interference from a cross channel. The disclosed UE device includes an array of K receive antennas for receiving one or more signals over a direct channel from a first transmitter having M transmit antennas and to receive one or more interfering signals over a cross channel from a second transmitter having M transmit antennas. In addition, the disclosed UE device includes a processor that configured to align interference from the one or more interfering signals over the cross channel by first estimating or computing a direct channel matrix and a cross channel matrix for the direct and cross channels, respectively, and then determining a rank d of the direct channel. The UE device also selects d predetermined vectors from a set of predetermined vectors having size M, where the set of predetermined vectors is known by the first and second transmitters and by any other user equipment devices affiliated with the first or second transmitters. In addition, the UE device computes a combining matrix as a product of an Hermitian of the d predetermined vectors and an inverse of the cross channel matrix. If the receive antenna count K at the UE device is less than the transmit antenna count M at the transmitter, the processor at the UE may be configured to compute the combining matrix by computing a combining vector

$$r^l = \frac{(v_{ref}^l)^H G^+}{\left\|(v_{ref}^l)^H G^+ G\right\|}, \; l = 1, \ldots, d,$$

where $(v_{ref}^l)^H$ is an Hermitian of an lth vector from the d predetermined vectors, G^+ is an inverse of the cross channel matrix, and G is the cross channel matrix. Alternatively, if K is less than M, the processor at the UE may be configured to compute the combining matrix by extending the direct channel matrix and cross channel matrix in a time or frequency domain to compute an aggregate direct channel matrix and an aggregate cross channel matrix which are invertible with a probability of almost one in a multipath rich propagation environment, and then computing the combining matrix as a product of an Hermitian of the d predetermined vectors and an inverse of the aggregate cross channel matrix. The combining matrix may be fed back to the transmitter along with channel quality indicator information. At the UE device, the CQI may be derived by computing an equivalent noise power indicator as a product, for each of the d predetermined vectors, of an Hermitian of the predetermined vector and an inverse of the cross channel matrix, and then an effective noise power indicator may be fed back to the transmitter. The UE device also

computes an equivalent direct channel matrix as a product, for each of the d predetermined vectors, of a complex transpose of each predetermined vector and an inverse of the cross channel matrix and the direct channel matrix. Finally, the UE device applies the combining matrix to decode rank d data signals received at the user equipment device to project all cross channel signals from the second transmitter to an Hermitian of the d predetermined vectors to reduce or eliminate interference from the second transmitter.

In yet still further embodiments, a computer program product is disclosed that includes a non-transitory computer readable storage medium having computer readable program code embodied therein with instructions which are adapted to be executed to implement a method for operating mixed rank user equipment (UE) and/or access device (e.g., radio access network, such as an eNB) to align interference between two transmitter or eNB stations, substantially as described hereinabove. As disclosed, the computer program controls the processor to perform processes at the UE and eNB devices for aligning interference by applying a plurality of linearly independent vectors $V_{ref}=\{v_{ref}^{1}, \ldots, v_{ref}\}$ and channel knowledge H, G from each transmitter at each UE to convert the cross channel interference to the predetermined vectors $(V_{ref}^{l})^{H}$ and compute and feedback equivalent channel matrix information $H_{i,j}^{eq}$ to its affiliated transmitter. With this information, each transmitter selects L_i receivers and constructs a transmitted signal by applying a selected precoding matrix. In selected embodiments, the computer program is embodied on a computer-readable non-transitory storage medium with program instructions for aligning interference from a cross channel by performing a sequence of steps. In the preliminary step(s), direct and cross channel matrices are estimated for the direct and cross channels to the receiver having K receive antennas from first and second transmitters having M transmit antennas. After determining a rank d of the direct channel, d predetermined vectors are selected from a set of predetermined vectors having size M, where the set of predetermined vectors is known by the first and second transmitters. Subsequently, a combining matrix is computed as a product of an Hermitian of the d predetermined vectors and an inverse of the cross channel matrix, and the combining matrix is applied to decode rank d data signals received at the receiver to project all cross channels from the second transmitter to the d predetermined vectors to reduce or eliminate interference from the second transmitter. In addition, the computer program is configured to align interference from the cross channel by feeding back to the first transmitter an equivalent direct channel matrix which is computed for each of the d predetermined vectors as a product of a complex transpose of each predetermined vector and an inverse of the cross channel matrix and the direct channel matrix.

In still further embodiments, a receiver scheduling method and apparatus are disclosed for selecting and scheduling a plurality of rank d receivers having K receive antennas to receive one or more data streams from a first transmitter having M transmit antennas while aligning interference from a second transmitter having M transmit antennas. As disclosed, the first transmitter assembles CDI and CQI values for each data stream to be sent to each of the plurality of rank d receivers, such as by receiving CDI and CQI values or indicators thereof in a feedback uplink signal from each of the plurality of rank d receivers. The CDI and CQI values associated with a data stream at a rank d receiver are each derived from at least an equivalent direct channel matrix computed from one or more predetermined vectors having size M which are applied to project all cross channels from the second transmitter to the one or more predetermined vectors to reduce or eliminate interference from the second transmitter. For example, the CDI value in selected embodiments may be computed for each data stream at a rank d receiver as

$$CDI^{l} \triangleq \frac{h^{l,eq}}{\|h^{l,eq}\|},$$

for l=1 . . . d, where $h^{l,eq}$ is the equivalent direct channel matrix for each of l data streams to be sent to said receiver that is computed by computing for each of the d predetermined vectors a product of (1) a complex transpose of each predetermined vector, (2) an inverse of a channel matrix for a cross channel from the second transmitter to said receiver, and (3) a channel matrix for a direct channel from the first transmitter to said receiver. In other embodiments, the CQI value may be computed for each data stream at a rank d receiver as

$$CDI^{l} \triangleq \frac{\|h^{l,eq}\|^{2} - |h^{l,eq} v_{ref}^{l}|^{2}}{\mathfrak{N}^{l,eff}},$$

for l=1 . . . d, where $h^{l,eq}$ is the equivalent direct channel matrix for each of l data streams to be sent to said receiver that is computed by computing for each of the d predetermined vectors a product of (1) a complex transpose of each predetermined vector V_{ref}^{l}, (2) an inverse of a channel matrix for a cross channel from the second transmitter to said receiver, and (3) a channel matrix for a direct channel from the first transmitter to said receiver, and where $\mathfrak{N}^{l,eff}$ is an effective noise power indicator. The first transmitter then selects a first rank d receiver from the plurality of rank d receivers by computing a weighted CQI value for each data stream and choosing a rank d receiver having the largest weighted CQI value. For example, the weighted CQI value may be computed as a product of a proportional fairness scheduling parameter and the CQI value for each data stream. The remaining receivers are then scheduled by sequentially selecting one or more rank d receivers from the plurality of rank d receivers by computing a measure of orthogonality with respect to any previously selected rank d receiver that is derived from at least the CDI values and choosing a rank d receiver having the largest measure of orthogonality with respect to any previously selected rank d receiver. For example, the rank d receivers may be sequentially selected by projecting, for each unselected receiver, the assembled CQI values over a defined sub-space spanned by CDI values of any previously selected receivers to generate a projection value, and then selecting a rank d receiver having the smallest projection value representing the largest measure of orthogonality value with respect to any previously selected rank d receiver. Alternatively, the rank d receivers may be sequentially selected by computing the measure of orthogonality, for each unselected receiver, as a product of a scheduling parameter associated with said receiver, one or more CQI values associated with said receiver, and an orthogonality measure derived from a projection of the assembled CQI values over a defined sub-space spanned by CDI values of any previously selected receivers to generate a projection value; and then selecting a rank d receiver having the largest projection value. With this approach, the scheduling scheme may be applied to a plurality of mixed rank or single rank receivers where one or more of the plurality of rank d receivers has a rank that is not fixed over time.

It should be understood that as used herein, terms such as coupled, connected, electrically connected, in signal communication, and the like may include direct connections between components, indirect connections between components, or both, as would be apparent in the overall context of a particular embodiment. The term coupled is intended to include, but not be limited to, a direct electrical connection.

Numerous modifications and variations of the present application are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the embodiments of the application may be practiced otherwise than as specifically described herein.

Although the described exemplary embodiments disclosed herein are described with reference to a new downlink multi-user MIMO interference alignment, the present disclosure is not necessarily limited to the example embodiments which illustrate inventive aspects of the present disclosure that are applicable to a wide variety of signaling schemes and applications. Thus, the particular embodiments disclosed above are illustrative only and should not be taken as limitations upon the present disclosure, as the disclosure may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Accordingly, the foregoing description is not intended to limit the disclosure to the particular form set forth, but on the contrary, is intended to cover such alternatives, modifications and equivalents as may be included within the spirit and scope of the disclosure as defined by the appended claims so that those skilled in the art should understand that they can make various changes, substitutions and alterations without departing from the spirit and scope of the disclosure in its broadest form.

What is calimed is:

1. A method for aligning interference at a rank d receiver of a plurality of receivers having K receive antennas caused by first and second transmitters each having M transmit antennas, wherein K is the number of receive antennas and wherein M is the number of transmit antennas and wherein M is at least two (2), the method comprising:

assembling at the receiver a first channel matrix for the first transmitter and a second channel matrix for the second transmitter;

computing an equivalent direct channel matrix from the first and second channel matrices and d predetermined vectors selected from a plurality of predetermined vectors having size M; and

applying a combining matrix to decode rank d data signals received at the receiver, where the combining matrix is derived from the d predetermined vectors and an inverse of the second channel matrix to project all cross channels from the second transmitter to the d predetermined vectors to reduce or eliminate interference from the second transmitter, wherein d is the rank of one or more data signals and wherein d is also a number of the predetermined vectors.

2. The method of claim **1**, where assembling the first channel matrix and the second channel matrix comprises:

receiving pilot signals from the first transmitter and the second transmitter; and

determining a direct channel matrix for the first transmitter and a cross channel matrix for the second transmitter based on the pilot signals.

3. The method of claim **1**, where computing the equivalent direct channel matrix comprises computing one or more equivalent direct channel vectors by computing for each of the d predetermined vectors a product of a complex transpose of each predetermined vector and an inverse of the second channel matrix and the first channel matrix.

4. The method of claim **1**, further comprising feeding back the equivalent direct channel matrix to the first transmitter.

5. The method of claim **1**, where each of the rank d data signals is precoded at one of the first or second transmitters with a precoding matrix for each receiver that is computed as a null space of the d predetermined vectors and an Hermitian of equivalent direct channel matrices of any other receivers affiliated with the same transmitter.

6. The method of claim **1**, where the plurality of predetermined vectors is known to each receiver affiliated with the first and second transmitters.

7. The method of claim **1**, where the plurality of predetermined vectors is a set of orthogonal basis vectors for an M-dimensional transmission space.

8. The method of claim **1**, further comprising feeding back one or more of a channel quality indicator (CQI), rank indicator (RI), and precoding matrix information (PMI) from the rank d receiver to the first transmitter.

9. The method of claim **1**, further comprising:

computing at the rank d receiver an equivalent noise power indicator for each of the d predetermined vectors; and

feeding back to the first transmitter an effective noise power indicator.

10. The method of claim **1**, where computing the equivalent direct channel matrix from the first channel matrix and the second channel matrix comprises:

for each of the d predetermined vectors, finding a combining vector r for each of d data streams which minimizes an Euclidean distance of an equivalent cross channel (rG) to an Hermitian of that predetermined vector if K is less than M; and

computing the equivalent direct channel matrix for each of the d data streams from the product of the combining vector r and the first channel matrix, wherein d is also a number of the data streams.

11. The method of claim **1**, where computing the equivalent direct channel matrix from the first channel matrix and the second channel matrix comprises:

extending the first channel matrix and the second channel matrix in time or frequency domain to compute an aggregate direct channel matrix and an aggregate cross channel matrix which are invertible with a probability of almost one in a multipath rich propagation environment if K is less than M; and

computing the equivalent direct channel matrix from the aggregate direct channel matrix and the aggregate cross channel matrix and the d predetermined vectors.

12. The method of claim **1**, where the rank d receiver has a rank that is not fixed over time.

13. A method for transmitting one or more signals from a first transmitter having M transmit antennas to one or more receivers affiliated with the first transmitter, where each of the one or more receivers has K receive antennas and receives interference from a second transmitter having M transmit antennas, wherein K is the number of receive antennas and wherein M is the number of transmit antennas and wherein M is at least two (2), the method comprising:

acquiring at the first transmitter an equivalent direct channel matrix from each of the one or more receivers;

selecting a subset of the one or more receivers to receive a signal from the first transmitter;

selecting a rank of the signal for each receiver; and

for selected receivers, applying a precoding matrix to the signal to be transmitted from the first transmitter, where the precoding matrix is derived from d_{max}^{i} predeter-

mined vectors and any equivalent direct channel matrix from the selected receivers affiliated with the first transmitter to reduce or eliminate interference to any receivers receiving signals from the first transmitter or from the second transmitter,wherein d_{max}^{i} is the number of predetermined vectors and any equivalent direct channel matrix from the selected receivers affiliated with the first transmitter.

14. The method of claim **13**, further comprising:

transmitting a transmit signal x =Vs to the selected receivers, where V denotes the precoding matrix and where s represents data symbols to be transmitted at the first transmitter in which s represents signals of determined ranks specific for each selected receiver.

15. The method of claim **13**, where acquiring the equivalent direct channel matrix from each of the one or more receivers comprises receiving the equivalent direct channel matrix from each of the one or more receivers in a feedback uplink signal.

16. The method of claim **13**, further comprising computing a precoding matrix for the selected receivers by computing a null space of the d_{max}^{i} predetermined vectors and a Hermitian of equivalent direct channel matrices of any other receivers affiliated with the same transmitter to effectively eliminate interference to any receiver receiving a signal from the first transmitter or from the second transmitter.

17. The method of claim **13**, where the d_{max}^{i} predetermined vectors are known to each receiver affiliated with the first and second transmitters.

18. The method of claim **13**, where the d_{max}^{i} predetermined vectors are a set of orthogonal basis vectors for an M-dimensional transmission space.

19. The method of claim **13**, where acquiring at the first transmitter the equivalent direct channel matrix from each of the one or more receivers comprises receiving an equivalent direct channel matrix that is computed at an affiliated rank d receiver from d predetermined vectors selected from a plurality of predetermined vectors having size M, a first channel matrix representing a direct channel to the affiliated receiver from the first transmitter, and a second channel matrix representing a cross channel to the affiliated receiver from the second transmitter.

20. The method of claim **13**, where acquiring at the first transmitter the equivalent direct channel matrix from each of the one or more receivers comprises:

receiving, from each of the one or more receivers affiliated with the first transmitter, d pilot signals in the direction of a transpose of d combining vectors computed as a product of the d predetermined vectors selected from a plurality of predetermined vectors having size M and an inverse of a cross channel matrix from the second transmitter, and

estimating an equivalent direct channel matrix for each of the one or more receivers from the received pilot signals.

21. A user equipment device configured to receive rank d signaling over a direct channel and align interference from a cross channel,wherein d is the rank of one or more data signals, comprising:

an array of K receive antennas for receiving one or more signals over the direct channel from a first transmitter having M transmit antennas and to receive one or more interfering signals over the cross channel from a second transmitter having M transmit antennas, wherein K is the number of receive antennas and wherein M is the number of transmit antennas and wherein M is at least two (2); and

a processor configured to align interference from the one or more interfering signals over the cross channel by:

computing a direct channel matrix for the direct channel and a cross channel matrix for the cross channel;

determining a rank d of the direct channel;

selecting d predetermined vectors from a set of predetermined vectors having size M, where the set of predetermined vectors is known by at least the first and second transmitters;

computing a combining matrix as a product of the Hermitian of the d predetermined vectors and an inverse of the cross channel matrix; and

applying the combining matrix to decode the rank d data signals received at the user equipment device to project all cross channel signals from the second transmitter to the Hermitian of the d predetermined vectors to reduce or eliminate interference from the second transmitter, whaerein d is also a number of predetermined vectors.

22. The user equipment device of claim **21**, where the processor is further configured to feed back to the first transmitter an equivalent direct channel matrix which is computed as a product, for each of the d predetermined vectors, of a complex transpose of each predetermined vector and an inverse of the cross channel matrix and the direct channel matrix.

23. The user equipment device of claim **21**, where the processor is further configured to feed back channel quality indicator information to the first transmitter by:

computing at the user equipment device an equivalent noise power indicator for each of the d predetermined vectors; and

feeding back to the first transmitter an effective noise power indicator.

24. The user equipment device of claim **21**, where the processor is configured to compute the combining matrix if K is less than M by computing a combining vector

$$r^{l} = \frac{(v_{ref}^{l})^{H} G^{+}}{\left\| (v_{ref}^{l})^{H} G^{+} G \right\|}, \; l = 1, \ldots, d,$$

where $(v_{ref}^{l})^{H}$ is the Hermitian of an lth vector from the d predetermined vectors, G^{+} is the inverse of the cross channel matrix, and G is the cross channel matrix.

25. The user equipment device of claim **21**, where the processor is configured to compute the combining vector if K is less than M by:

extending the direct channel matrix and the cross channel matrix in a time or frequency domain to compute an aggregate direct channel matrix and an aggregate cross channel matrix which are invertible with a probability of almost one in a multipath rich propagation environment; and

computing the combining matrix as a product of the Hermitian of the d predetermined vectors and an inverse of the aggregate cross channel matrix.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO.	: 9,331,765 B2
APPLICATION NO.	: 13/822661
DATED	: May 3, 2016
INVENTOR(S)	: Amin Mobasher et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the claims

Claim 24, Column 38, Line 48 replace "1th" with --Ith--

Signed and Sealed this
Twenty-fifth Day of October, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office